Human Reliability Assessments for the Maintenance Operation of Marine Systems

By

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Abstract

Human intervention plays a critical role in the maintenance operations of marine systems. Consequently human factors are identified as one of the main causes of accidents in marine systems especially during maintenance operations. Characterisation and assessments of human factors in the form of Human Reliability Assessment (HRA) is an important step to better understand accident causation during maintenance operations. This would help minimize human errors and enhance overall safety and reliability of the marine systems. The International Maritime Organization (IMO) recommends implementing HRA to quantitatively assess the effect of human errors as a part of quantitative risk analysis of shipping operations. However, HRA for the maintenance operations of marine systems is not given due attention. This PhD research is focused on developing novel methodologies to accurately estimate the Human Error Probability (HEP) during the maintenance operations of marine systems. The developed methodologies will help in better understanding accident causation, estimation of HEPs, and to develop the required strategies to minimize the HEP.

This thesis contains seven chapters. The first chapter provides the introduction and general structure of the thesis. Second chapter presents development of a novel methodology to assess the HEP for the maintenance operation of marine systems. The developed methodology is applied to the maintenance procedures of a marine engine as a case study. The results showed that among the 43 considered activities, ‘inspection and overhaul of piston/piston rings’ have the lowest HEP meaning it has a low consequence for accidents. On the other hand, ‘fuel and lubricating oil filters pressure difference checking’ and ‘renew filter element’s activity have the highest HEP indicating it has highest chances of accidents. The third chapter presents a novel monograph as an easy-to-use tool to estimate HEP for marine operations. The developed monograph is applied to the maintenance procedures of a High Pressure (HP) fuel pump for estimating HEP. The results showed that ‘inspection of fuel injectors’, ‘renewing nozzles’ and ‘testing’ has the highest HEP. While the fourth chapter proposes a novel technique by revising and modifying the Human Error Assessment and Reduction Technique (HEART) to assess the HEP during the maintenance activities in marine operations. The developed methodology is applied to the maintenance procedures of a marine engine exhaust turbocharger as a case study. Application of the developed

methodology confirms that extreme weather condition, extreme workplace temperature, high ship motion, high level of noise and vibration, and work overload and stress all increase the likelihood of human error as well as likelihood of potential accidents. The fifth chapter presents development of an HEP assessment technique using an advanced probabilistic technique named Bayesian Network (BN). The developed methodology is tested on the maintenance of marine engine's cooling water pump for engine department and anchor windlass for deck department. The case study results showed that category "A" chief engineer/captain (highest rank) with 10 years or more experience and voyage duration of 1 month has the lowest HEP, and category "D" fourth engineer/third officer with 5 years' experience and voyage duration of 4 months has the highest HEPs. As part of the HRA, extensive data collection activity was conducted. The details of this activity and outcome are reported in this thesis. The collected data is analysed for normality and also pair-wise significance test and presented in chapter 6. It helps to study generalization of the data and also to identify the relative importance of the factors. Workload and stress, and ship motion (roll and pitch) are identified to be critical factors affecting human performance on on-board maintenance operations. The collected data played an important role in testing and verifying earlier developed techniques and models. Chapter 7 includes the conclusions of the thesis.

This thesis aims to serve as a comprehensive source of knowledge and technique to form a better understanding of human factors associated with maintenance activities in marine operations. It will assist in ensuring implementation of IMO requirement for safe and reliable maintenance activities and marine operations.

Keywords: Reliability assessment, Maintenance operation, Marine system, Human factors, Human error probability, Environmental and operational conditions, Surveying, Data collection.

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Declaration and Statements

Declaration of Originality

I declare that this is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been duly acknowledged in the text and a list of references if given.

Signature: ____________ Date: 27/04/2017

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Statement of Ethical Conduct

To develop the methodologies and tools data collection from the seafarers around the globe was required in this PhD research. Therefore, a human research ethics approval was obtained from the University of Tasmania's human research ethics committee (Ethics Ref No: H0015701).

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- All of my family members and relatives;

- And finally, all my friends for their companionship.

Dedication

This thesis is dedicated to my beloved parents **Alhaj Sirajul Islam Talukder, Alhaj Hafiza Islam Talukder** and beloved **Teachers**.

“Who blessed me with their knowledge and invaluable support at all time”.

Thesis by Journal Articles

The following two published, one accepted and two under review journal articles constitute the content of this thesis.

- Chapter 2: **Islam, R.,** Abbassi, R., Garaniya, V., and Khan, FI. (2016). Determination of human error probabilities for the maintenance operations of marine engines. Journal of Ship Production and Design, 32, 1-9. doi:10.5957/JSPD.32.2.150004.

- Chapter 3: **Islam, R.,** Yu, H., Abbassi, R., Garaniya, V., and Khan, F. (2016). Development of a monograph for human error likelihood assessment in marine operations, Safety Science, 91, 33–39. doi:10.1016/j.ssci.2016.07.008.

- Chapter 4: **Islam, R.,** Abbassi, R., Garaniya, V., Khan, F., 2017. Development of a Human Reliability Assessment Technique for the Maintenance Procedures of Marine Operations. Journal of Loss Prevention in the Process Industries (Submitted, Under review)

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Co-Authorship for Journal Articles

Dr Yu has contributed in developing the monograph along with other authors for the journal article in chapter two. Remain journal articles co-authorship are as follows:

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List of Abbreviations

HRA: Human Reliability Assessment

IMO: International Maritime Organization

HEP: Human Error Probability

BN: Bayesian Network

TSB: Technology Safety Board

MD: Marine Department

MARS: Mariners Alerting and Reporting Scheme

ABS: American Bureau of Shipping

MAIB: Marine Accident Investigation Branch

ATSB: Australian Transportation Safety Bureau

SLIM: Success Likelihood Index Method

THERP: Technique for Human Error Rate Prediction

HEART: Human Error Assessment and Reduction Technique

PSF: Performance Shaping Factors

SLI: Success Likelihood Index

APOA: Assess the Proportion of Affect

PMS: Planned Maintenance System

IACS: International Association of Classification Societies Ltd

ISM: International Safety Management Code

HP: High Pressure

EPC: Error-Producing Condition

HT: High Temperature

HSE: Health and Safety Executive

LT: Low Temperature

COC: Certificate of Competency

CASA: Civil Aviation Safety Authority

IES: Illuminating Engineering Society

DMA: Danish Maritime Accident

STCW: Standards for Training, Certification, and Watchkeeping

EIF: Error Influencing Factor

MIF: Motion Induced Fatigue

SAPOE: Seafarers Assessed Proportion of Effect

ED: Engine Department

DD: Deck Department

UK: United Kingdom

PI: Protection and Indemnity

CPT: Conditional Probability Table

GEP: Generic Error Probability

GT: Generic Task

US: United States

AMSA: Australian Maritime Safety Authority

DBN: Dynamic Bayesian Network

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1. Introduction

1.1 Background

Maintenance of marine systems is significantly important as it prevents unexpected down time, reduces the number of accidents and also helps to extend the life of the machinery. However, faulty maintenance may lead to marine accidents. The main consequences of marine accidents are fire and explosion which can result in loss of life, major injury to any person on-board, actual or presumed loss of a ship, her abandonment and material damage (Kuehmayer, 2008).

Several catastrophic accidents have occurred around the world due to failure of the maintenance operation of marine systems over the past few decades. In 1994, a Canadian fishing vessel "RALI II" was returning from the fishing grounds to shore when a component of fuel filters of the main engine failed while the engine-room personnel were cleaning the filters. The improper approach used for cleaning the fuel filter caused the diesel fuel to splash on to unprotected exhaust pipes and created the fire. As a result of this accident, the engine-room sustained considerable damage but fortunately there were no injuries (TSB, 2013). Likewise, a Hong Kong registered ship was routing from China to India, when the third engineer replaced the filter element but did not follow the instructions provided by the manufacturer. In addition, the engineer used improper tools and forgot to bleed off the air from the lubricating oil filter after replacing it. The air plug of the lubricating oil filter came off and the oil spurted on to the hot exhaust pipe and caused a fire. In this incident, the engineer suffered serious injury and the accident caused serious damage to the engine room (MD, 2011). Another example is an accident which occurred during the preventive maintenance of an auxiliary engine in the Coral Sea in 2001. During the investigation, it was found that as per the normal maintenance operation, all the main bearings of the engine were renewed but without following any systematic investigation procedure. This incorrect maintenance operation caused all the connecting rods to become unusable. As a result, the shipping company incurred an unplanned expenditure of nearly US$100,000

(MARS, 2010). These aforementioned accidents demonstrate the necessity to reduce shipping accidents caused by maintenance operations of marine systems.

Most on-board maintenance operations are conducted in challenging working conditions. The complexities of tasks and design of the equipment being maintained strongly influence the performance of maintenance operations. Poorly assembled and difficult to maintain equipment are contributors to maintenance errors. Moreover, broad organisational factors such as poor communication, inadequate systems monitoring and not learning from previous incidents can result in human error. On the other hand, social issues such as the lack of appreciation from higher management for high quality maintenance operations and extra work pressures can also lead to errors occurring. Lack of adequate training, unfamiliar equipment, not following the procedural documentation, and adverse working environment in which the maintenance activities are performed can also be causes of error during maintenance activities. According to Pennie et al. (2007) the human factor in marine operations accounts for 75-96% of maritime casualties. Human factor issues such as poor maintenance, lack of back-up systems and crew fatigue may also lead to a dangerous work environment. Even if the error does not lead to a catastrophic accident, injuries or loss of life, it can still make notable economic impacts because of delayed operations.

According to the American Bureau of Shipping (ABS) approximately 50% of maritime accidents are initiated by human error, while 30% of maritime accidents occur due to failures of humans to avoid an accident (ABS, 2003). It is noted that there is a consistency of cause factor findings among the data and reports within Australia, Canada and the UK (ABS, 2003). According to the Marine Accident Investigation Branch (MAIB) UK, the Australian Transportation Safety Bureau (ATSB), and the Transportation Safety Board of Canada (TSB), overall marine accidents directly associated with the occurrence of human errors are 82%, 85% and 84% respectively (ABS, 2003). Across all marine accidents, previous investigation by the ATSB, TSB and MAIB demonstrated that maintenance related human error accidents are 3%, 12% and 1% respectively, of the total marine accidents (Baker and Seah, 2004). It is clear that human error is a significant cause of many accidents in the shipping industry. Needless to say whenever there is human involvement, human error is unavoidable and there should be proper management to reduce this human error as much as possible. Many of the human factor related issues in maintenance activities are underlying challenges and can be addressed, but a systematic approach for identifying and addressing them is required. Attention to human factors is a proven way to enhance performance and reduce the risk of incidents and accidents in the shipping industry.

The estimation of Human Error Probability (HEP) is a key to HRA. For quantitative assessment of human error likelihood, it is necessary to estimate the HEP. The estimated HEP values indicate the level of human error likelihood in a particular maintenance operation. To quantify the risk of maintenance operations of marine systems, it is necessary to estimate the HEP. The importance of HEP estimation is to obtain a more desirable understanding of human error and the consequences. There are a few well-known techniques available to estimate the HEP such as Technique for Human Error Rate Prediction (THERP), Success Likelihood Index Method (SLIM) and Human Error Assessment and Reduction Technique (HEART) (Kirwan, 1994). Moreover, the advanced probabilistic technique Bayesian network (BN) is also available for HEP estimation.

THERP is one commonly applied method in probabilistic safety assessment (Jae and Park, 1995). This method has limited usefulness in error reduction as it does not present sufficient guidance in modelling both scenarios and the impact of Performance Shaping Factors (PSF) on error. On the other hand, SLIM is based on presumably independent PSF and it is hard to confirm whether the PSF are independent. However, it is a simple and flexible method. HEART is quite subjective and reliant on the experience of the analyst but, it is a technique for comparing HEP and is based on the degree of error recovery. It is also easy to understand, is fast and also reliable (Casamirra, 2009). BN can provide fast responses to queries and has the dynamic updating capability when new information is available (Musharraf et al., 2013).

DiMattia et al. (2005) applied SLIM to estimate the HEP for offshore platform musters and Noroozi et al. (2013) for the pre- and post-maintenance procedures of process facilities.

In another study, Noroozi et al. (2014) applied HEART to estimate HEP for offshore oil and gas facilities. BN have been applied in various industries for assessing the HEP (Groth and Mosleh, 2011; Heckerman et al., 1995; Mu et al., 2015; Musharraf et al., 2013). Groth and Mosleh (2011) applied BN for predicting HEP in the nuclear power industry. Mu et al. (2015) applied BN in predicting the HEP in the aviation industry. (Musharraf et al., 2013) applied BN to human reliability assessment during evacuation in offshore emergency conditions. These applications demonstrate the importance of human error determination in the maintenance procedures of any process facilities and engineering operations including marine operations. However, estimation of HEPs in maintenance operations of marine systems has not received enough attention despite the major action taken during the maintenance procedures in other sectors. Moreover, International Maritime Organization (IMO, 2002) guidance, proposed to adopt HRA for shipping industry. Furthermore, it is also highly necessary for maritime authorities to collect near miss and human error data. There is a lack of comprehensive methodology to estimate the HEP for maintenance operations of marine systems. It is still challenging to model human error for the shipping industry which requires further research.

Based on the on-board maintenance scenarios SLIM, HEART and BN have been considered in this research to develop novel methodologies and tools to estimate HEP for the maintenance operations of marine systems. The methodologies and tools developed in this PhD research can be applied to maintenance operations on any equipment and systems on-board ship.

1.2 Research objectives and Research Questions

The primary objective of this PhD thesis is to develop techniques and tools that enhance safety and reliability of the maintenance operation of marine systems. This is addressed through the following objectives:

- to develop novel and dynamic methodologies to accurately estimate the HEPs during the maintenance operations of marine systems;
- to implement the methodology as an easy-to-use tool to estimate the HEP during the maintenance operations;

- to develop an HRA technique for fulfilling the recommendation of IMO guidance implementing HEART;
- to develop a Human error assessment technique with dynamic updating capability;
- to test collected survey data for identifying the characteristics and relative importance of the seafarers' performance-affecting factors; and
- to implement the newly developed methodologies in real life applications.

Moreover, each objective is accomplished by answering a relevant research question. These questions are recorded below.

- How to develop a human reliability assessment technique in particular for the maintenance operations of marine systems?
- How to develop a user-friendly tool for chief engineers or captains in the instant decision-making process for various scheduled and unscheduled maintenance operations?
- How to fulfil the recommendation of International Maritime Organization (IMO) guidance for implementing HEART to estimate HEP?
- How to develop a human error assessment technique with dynamic updating capability?
- How to identify the characteristics and relative importance of the seafarers' performance-affecting factors from collected survey data?

1.3 Scope and limitations

The focus of this PhD research is to develop new methodologies and tools for HRA for the maintenance operations of marine systems. The methodologies and tools are developed based on the opinion from experienced seafarers who are responsible for maintenance operations on board ship. The scope of this research is firstly to identify the factors that affect seafarers' performance during the maintenance operations of marine systems. Secondly it is to investigate the available HRA techniques. Finally, it is to develop new methodologies and tools to estimate the HEP for the maintenance operations of marine systems. The first methodology is developed by modifying the existing expert judgment method SLIM due to the lack of human error data for the maintenance operations of marine systems. This methodology is applied to estimate HEP for the maintenance operations of various systems and equipment of a marine engine. The case study results are then used to develop a novel monograph as an easy-to-use tool for quick HEP estimation. The second technique is developed by revising conventional HEART to fulfil the recommendation of IMO guideline for HRA. To develop this methodology, required data collection by conducting a questionnaire survey among experienced seafarers around the world. This technique was developed considering factors that affect seafarers' performance due to marine environmental and operational conditions as well as with individual factors. None of the above-developed methodologies and tools has the capability of updating probability when new information is available. Therefore, the third technique is developed based on the advanced probabilistic technique BN to estimate HEP more accurately and reanalyse posterior HEP instantly based on the newly available information. The developed methodologies and tools can be applied to container ships, bulk carriers, tankers, ferries, cruise ships, fishing vessels, anchor handling and supply vessels and salvage tugs to estimate HEP during maintenance operations.

The methodologies and tools developed in this study do not consider organisational factors (i.e. crew complement and company policies) although these factors also affect seafarers' performance. Moreover, in this study methodologies and tools are developed considering seafarers' performance static though the human performance varies with time. Lastly, the methodologies and tools in this study are not developed particular to the ship type or size because the seafarers' opinion, collected to develop methodologies and tools from the numerous seafarers around the world, have experienced performing maintenance operations on various types and sizes of ships. It was not categorised specific to ship type nor size due to lack of such information. However, the development of HRA methodology and tools specific to ship type/ size could be helpful for more accurate HEP estimation because the type and size of a ship may affect seafarers' performance differently. For example, ship motion affects seafarers' performance more in a small length ship compared to a large ship. On the other hand, in tanker vessels, cargo vessels and fishing vessels, the seafarers' performance is affected differently due to the nature of these ship types.

1.4 Organization of the thesis

This thesis is written in manuscript format (paper-based). A summary of the thesis outline is provided in the section below. To a large extent these chapters are independent and can be read individually.

Chapter 2: Determination of Human Error Probabilities for the Maintenance Operations of Marine Engines

This chapter presents the development of a comprehensive methodology to assess the HEP during the maintenance operations of marine systems. The developed methodology is applied to the maintenance procedures of a marine engine as a case study. The high risk human error related activities are identified and appropriate measures suggested to reduce the HEPs.

Chapter 3: Development of a monograph for human error likelihood assessment in marine operations

Chapter 3 explores the development of a novel monograph. It is an easy-to-use tool to estimate HEP during maintenance activities of marine operations. The unique monograph is user-friendly and a capable tool for estimating the HEPs instantly rather than following the step by step procedures. This well-defined monograph will help the chief engineer or captain in quick human error assessment and help in the decision-making process for various scheduled and unscheduled maintenance operations.

Chapter 4: Development of a Human Reliability Assessment Technique for the Maintenance Procedures of Marine Operations

Chapter 4 proposes an HRA technique for maintenance operations on-board ships. The proposed technique fulfils the recommendation of IMO guidance implementing HEART for assessing the effect of the HEP. This study is very useful for the classification societies. It provides simple and easy to use procedures to evaluate the HEPs during the maintenance operations of marine systems.

Chapter 5: Human Error Probability Assessment during Maintenance activities of Marine Systems

Chapter 5 provides HEP assessment technique during maintenance activities of marine systems using an advanced probabilistic concept named BN. The developed technique has the capability of dynamic updating and root cause analysis. This work is very helpful in designing effective and efficient maintenance operations. It also identifies the key variables required to be maintained for safe and reliable maintenance operations.

Chapter 6: Human Error Assessment during Maintenance Operations of Marine Systems - What is Important?

Chapter 6 presents data collection and analysis procedures for maintenance operations of marine systems. The collected data is run through a range of tests. It helps to study the generalization of the data and also to identify the relative importance of the factors. The collected data plays an important role in testing and verifying earlier developed techniques and models.

Chapter 7: Conclusions

This final chapter summarizes the major findings of this PhD research and points out several new directions for future research.

Appendices

The appendices contain survey questionnaire, collected raw data, CPT, “t- testing” results, normality test results, ethics approval and other ancillary information.

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Islam, R., Abbassi, R., Garaniya, V., Khan, F. I. 2016. Determination of human error probabilities for the maintenance operations of marine engines, Journal of ship production and design, 32(2), 1-9. doi:10.5957/JSPD.32.2.150004

3. *Development of a Monograph for Human Error Likelihood Assessment in Marine Operations*

Abstract

Human error is a dominant factor in marine operations, on a daily basis many accidents occur due to human error during maintenance activities of ships. Assessment of the likelihood of human error is essential to minimize accidents and incidents during maintenance operations of marine engines. Most of the current techniques to estimate Human Error Probability (HEP) require significant technical and manpower (expert) resources. The main aim of this study is to develop a monograph for assessing the likelihood of human error in marine operations that can be applied for instant decision making. Due to the lack of human error data for marine operations, the Success Likelihood Index Method (SLIM) is used to estimate HEP. The developed monograph can be helpful for chief engineers or captains in the decision making process for various scheduled and unscheduled maintenance operations. This monograph could also be used as guidance for ship owners, operators, masters and classification societies to better prepare, prioritise and sort maintenance activities for safe and reliable marine operations. It can serve as a helpful tool to reduce the potential of accident occurrence.

Keywords: Monographs, Success Likelihood Index Method, Human Error, Maintenance activities, Marine operations.

3.1 Introduction

Humans are liable to make errors and this is unavoidable. In operational activities of ships, maintenance is one of the most critical operations. Marine maintenance operations are totally reliant on humans. The literature suggests that many accidents and incidents in the past have occurred due to human error such as in Erika, Costa Concordia and “RALI II” (DMA, 2011; Schröder-Hinrichs et al., 2012; TSB, 2013). Most on-board maintenance is conducted under challenging working conditions. The task plan and design of the equipment being maintained strongly influences the performance of maintenance activities. Incorrectly assembled and difficult to maintain equipment is another contributor to maintenance errors (Pennie et al., 2007). Moreover, broad organisational factors such as poor communication, inadequate system monitoring and failure to learn from previous maintenance errors can result in human error. On the other hand, societal issues such as lack of appreciation from higher management for high quality maintenance operations and extra work pressures can also lead to the occurrence of errors. Lack of adequate training, uncomfortable equipment, failing to follow procedural documentation and adverse working environments in which maintenance activities are performed, are also primary causes of maintenance error. According to Pennie et al. (2007), the human factor in marine operations accounts for 75-96% of maritime casualties. Human factor issues such as poor maintenance, lack of back-up systems and crew fatigue may also lead to a dangerous work environment. Human error could lead to catastrophic accidents as demonstrated in the sinking of the Prestige tanker near the coast of Galicia (Spain). Even if an error does not lead to a catastrophic accident, injuries or loss of life, it can still make notable economic impacts due to delayed operations (Pennie et al., 2007). Shipping is a safety critical industry and there are numerous causes for human error in marine operations. Some of the most common reasons are lack of training, lack of work experience, fatigue, communication and the cultural differences of seafarers. These factors are discussed in more detail in the next few paragraphs.

Training is the expansion of knowledge through instruction. Here, it is associated with an individual’s capability to most competently define and accomplish the essential actions required to complete maintenance activities of marine on-board operations. Previous studies by Embrey et al. (1984); Noroozi et al. (2013) suggest that training is one of the most important performance shaping factors (PSFs) in the maintenance procedures of offshore activities. The International Convention on Standards of Training, Certification and Watchkeeping (STCW) has set out a mandatory standard for seafarers to accomplish their responsibilities. However, the standards of training set out in STCW are a minimum set (Squire, 2005). Lack of training can be one of the causes for human error in marine operations (Squire, 2005). On the other hand, seafarer training is generally provided on shore (Colleges/ Universities) rather than on training ships. This could be a hurdle in providing appropriate knowledge. Training ships play a vital role in seafarers training. Through training on a training-ship, seafarers can comprehend the importance of working on board and witness complete procedures of the ship's operation which in turn can motivate them to work harder and attain more exact knowledge. It is evident in the literature that many fresh theoretically qualified seafarers have a lack of practical skills despite having followed an approved training course, and this is also a factor in human error in marine operations (Phil Deegan, 2011).

Likewise, experience comes from practical contact with, and observation of, procedures. It is defined as the practical knowledge of the maintenance activities of on-board marine operations. One individual may not be as highly trained as other individuals, but may have practical experience about the maintenance activities of marine operations and the stressors that accompany real events. Lack of experience is another reason for human error in marine operations. For example, seafarers working on a container ship when changing to another ship (i.e. bulk carriers) which may not have the same systems, may lack knowledge of the different systems of the new ship. Another issue is technology advancement of the systems and equipment where new requisites need to be understood as seafarers may not be able to utilise their prior experience on new systems. Phil Deegan (2011), a chief engineer suggested that a third engineer with very little experience of machinery operation or maintenance, could become a source of human error in marine operations.

Fatigue is extreme tiredness arising from mental/physical exertion or illness. It is one of the major causes of human error and has contributed to 16% of vessel casualties and 33% of injuries in the maritime industry (Grabowski et al., 2009; Margetts, 1976;

Rothblum, 2000). There are various causes of fatigue in marine operations including lack of sleep, stress, boring/repetitive work, noise/vibration, inadequate ventilation, poor lighting, excessive heat/cold, poor air exchange and ship movement. Food (timing, frequency, content and quality), the effects of alcohol, drugs and caffeine, excessive workload, illnesses, poor workspace design and poor shift scheduling are additional causes of fatigue. Fatigue directly affects seafarers' performances by causing inability to concentrate on work, diminished decision making ability, decreased memory, and changed mood and attitude. Likewise, faintness, headaches, heart palpitations, insomnia, loss of appetite, rapid breathing, and inadequate shift scheduling are also causes of fatigue (Squire, 2013). Moreover, seafarers spending long periods of time at sea and performing maintenance work in a challenging environment causes human error in marine operations. The ultimate consequences of fatigue in marine operations are accidents, economic loss, environmental damage, injury, poor health and poorer performance.

Communication is conveying or exchanging information by speaking, writing, or using some other medium. Clear communication (simple language instead of complicated jargon) is essential for safe work in marine operations. It is also a required practice in marine operations to ensure correct understanding of human behaviour at work, but humans rarely follow the practice as it is only an option (Murphy, 2006). The ability to accurately convey information by word of mouth or written communication is important not only for the safety of seafarers, but also for their wellbeing. Some seafarers have a poor language level and hence they face difficulty communicating with colleagues. Communication is not only talking, reading and writing procedures but also the exchange of ideas, information and knowledge between individuals (Murphy, 2006). Poor communication globally among seafarers and the challenge of communication between on-shore and off-shore maintenance operators is another cause of human error in marine operation (Pennie et al., 2007).

Cultural differences are variations in the way of life, beliefs, traditions and laws between different countries, societies and people. Seafarers' background cultures may affect their comprehension and cause human error (Lewis, 2010). Cultural variances are mostly relevant in marine operations due to the engagement of people from many seafaring nations. Cultures tend to diverge in numerous substantial ways. These variances not only sensitise people in different ways, but also affect their understandings of people from other cultures. Some seafarers from Germany, Scandinavia, America, Canada, Australia and Britain tend to pay attention and emphasis on one thing at a time (Lewis, 2010). They like to stick to plans, focus on the facts, and rely on statistical information and reference materials to stay focused. They tackle problems with logic, use nominal body language to communicate with their colleagues. Also some seafarers with different cultural backgrounds such as Japanese, Chinese, Taiwanese, Koreans and Filipinos like to be holistic, subtle and perceive an unfolding schedule of events. They humbly listen to people while paying attention to the whole image in order to agree upon small corrections. They use evidence obtained from reference books and direct contact with people. They avoid conflict, use fine body language (i.e. nods and slight movements) and pay attention to protecting their colleagues from losing face (Murphy, 2006). Seafarers from cultures such as India, Pakistan, Polynesia and Mediterranean populaces however, like to be involved in many things at once. They do not easily lose face simply since failure tends to be attributed to situations rather than to people. These cultural factors are also some reasons for human error in marine operations.

Many of the human factor related issues in maintenance are underlying issues and so can be addressed, but a systematic approach for identifying and addressing them is required. Attention to human factors is a proven way to enhance the performance and reduce the risk of accidents and incidents in marine industries. For quantitative assessments of human error likelihood, it is necessary to estimate HEP. HEPs are estimated based on factors that affect human performance, known as PSFs. A PSF is one aspect of an individual's characteristics, environment, organization, or a task that particularly impacts on human performance and the likelihood of human error. The estimated HEP value indicates the level of human error likelihood in a particular operation.

The Human Error Assessment and Reduction Technique (HEART), the Technique for Human Error Rate Prediction (THERP) and the Success Likelihood Index Method (SLIM) are the most common methods for human error likelihood assessments (Kirwan, 1994). The HEART methodology is easy to comprehend, fast and trustworthy, but it is relatively subjective and heavily dependent on the experience of the analyst (Casamirra, 2009; Noroozi et al., 2014a). On the other hand, THERP is the most common method for probabilistic human error assessment. However, the effectiveness of this method is restricted to error reduction and it does not offer enough guidance for modelling the impacts of PSFs and scenario development (Jae and Park, 1995). Finally, SLIM is one of the better known methodologies for estimating HEP based on expert judgment. Many other researchers (Deacon et al. (2013); Dhillon (1987); DiMattia (2004); Noroozi et al. (2013)) have applied this technique in different industries. DiMattia (2004) applied this method to estimate HEP for offshore platform musters, while Noroozi et al., (2013) applied it to pre- and post-maintenance procedures of process facilities and Islam et al. (2016a) applied it to maintenance operations of marine engines.

Previous applications of SLIM have demonstrated that one can rely on an expert judgment approach when there is a lack of sufficient data (DiMattia, 2004; Khan et al., 2006; Noroozi et al., 2013). However, estimating the HEP in SLIM methodology requires accessing different technical and manpower (expert) resources. Also, the lack of use of SLIM in marine operations is due to the fact that the chief engineer or captain has to follow a step by step procedure to estimate the HEP, which requires lengthy decision making. Time during ship operations is critical. Therefore, there is a need to develop a user-friendly methodology to estimate HEP instantly, considering the existing operational and environmental factors affecting seafarers' performance in marine operations. However, the development of a quick and user-friendly solution to estimate the HEP instantly is challenging. This challenge motivated the authors to undertake the present study. The objective of the current study is to develop a monograph for human error likelihood assessment during the maintenance operations of a ship. This monograph can allow instant decision making during maintenance activities related to on-board marine operations. According to the estimated HEP value, maintenance activities could be well prepared, prioritised and consequently systematized to enrich the overall safety and reliability of maintenance activities. In this study, the SLIM is adopted and applied to develop a monograph. This monograph can significantly decrease the time and resources required to estimate HEP whilst decision making for marine operations involving different environmental and operational conditions.

3.2 Methodology for a Human Error Likelihood Monograph in Marine Operations

SLIM has the potential to overcome problems of unpredictability in multiple expert judgments or problems concerning systematic consideration of PSFs. The basic principle of this method is the likelihood of particular error occurrence in a specific situation in combination with the effect of a relatively small set of PSFs (Raafat and Abdouni, 1987).

The likelihood of human error depends on the effect of human performance commonly called PSF. A PSF is the factor relating to an individual’s environment or activity that affects performances positively or negatively. The PSF encompass those influences that enhance or degrade human performance. Based on the nature of maintenance activities and external environmental factors, various PSFs can be shortlisted and selected by the chief engineer or captain.

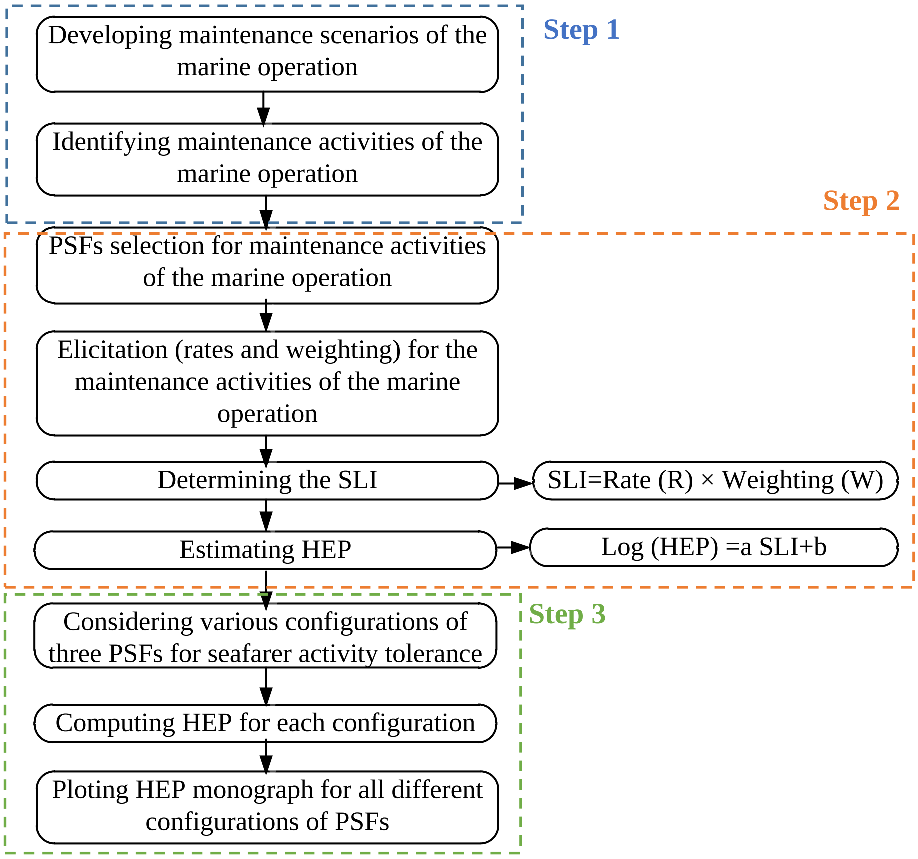


Figure 3-1: Methodology of Human Error Likelihood Monograph for Marine Operations

Steps to develop the human error likelihood monograph for marine operations by applying SLIM are illustrated in Figure 3-1.

3.2.1 Task analysis (step 1)

The first step of the methodology is development of the maintenance scenarios and identifying the maintenance activities of marine operations. Generally, there are two types of maintenance in marine operations, planned and preventive. Preventive maintenance in marine operations is selected as a scenario in this study. According to the preventive maintenance scenario in marine operations, marine engine maintenance activities are considered in this study. The considered activities are related to the maintenance of various systems and equipment of marine engines such as fuel and lubricating system, air starting, cooling and exhaust system, fuel injection and control system, engine block with bearings, cylinder head with valves, and piston, liner, connecting rod, crankshaft , camshaft and valve drive mechanism. A total of 43 important maintenance activities are considered from the above mentioned system and equipment of marine engines. Details of these maintenance activities are mentioned in Islam et al. (2016a).

3.2.2 HEP computation (step 2)

In the second step of the methodology, training, experience, and fatigue are considered as a PSF. According to expert opinions these are the most important PSFs of maintenance activities in marine operations.

Due to the lack of HEP data in marine operations, an expert judgement technique is used in this study. A panel of judges was selected for the appropriate data (e.g. selection, rating and weighting of PSFs). The rating of PSF is a measure of the importance of that PSF. Rating is very important for calculating SLI in SLIM process. PSF rating selected in this study ranges from 0 to 9, where 9 is the maximum and 0 is the minimum value. The rating is determined for each of the three selected PSFs and 43 important maintenance activities in marine operations. The SLIM process also requires weighting those PSFs to develop a Success Likelihood Index (SLI). In this study, weighting and rating data are taken from three expert judges with a wide range of knowledge and experience in maintenance in marine operations. After collecting the rating and weighting data, the final step is performed to estimate the HEP. The rating of each activity multiplied by the weighting is considered as an SLI for the given PSF. After acquiring SLI for each activity, HEP was estimated as shown in Figure 3-1. Further, the constants 'a' and 'b' are required to evaluate the HEPs for the activities with the lowest and highest SLI values. These constants are calculated using the lowest and highest HEPs (10^{-5} and 0.15) values and relevant SLIs. The final equation is demonstrated as:

$$\text{Log (HEP)} = -0.16367 \text{ SLI} - 0.27142 \qquad \textbf{[3-1]}$$

Using Equation 3-1, the HEP values are estimated for 43 considered maintenance activities.

3.2.3 Globalising HEP to all possible configurations (step 3)

From the mean HEP value of 43 maintenance activities in marine operations, one thousand (10x10x10) data samples were generated which correspond to all possible configurations of values for three PSFs. The HEP value is estimated for each configuration. In total, 1000 HEP values are estimated. Subsequently, these PSFs together with their HEP values are employed to generate the human error likelihood assessment monograph as shown in Figure 3-2. This monograph can serve as an effective tool for fast and accurate estimation of HEP values during maintenance activities in marine operations.

An example is provided below to demonstrate how the experts' opinions (linguistic) and deterministic score are considered in estimating human error and how the results are interpreted.

A seafarer having more than 5 years' experience in marine operations is considered to be an experienced seafarer. This experience category would fall into the rating level 7 on scale of 0-9. Considering this rating along with importance of PSF, HEP is estimated as 0.001. This signifies that there is possibility of one failure caused by human error in 1000 attempts. This value is lower compared to an inexperienced seafarer (having less than a year of experience), who is likely to make one error in 50 attempts. This method provides a clear understanding of how experience improves chances of minimizing human error.

3.3 Human Error Likelihood Monograph for Marine Operations to estimate HEP

The monograph can serve as an effective tool for fast and accurate estimation of HEP values during maintenance activities of marine operations.

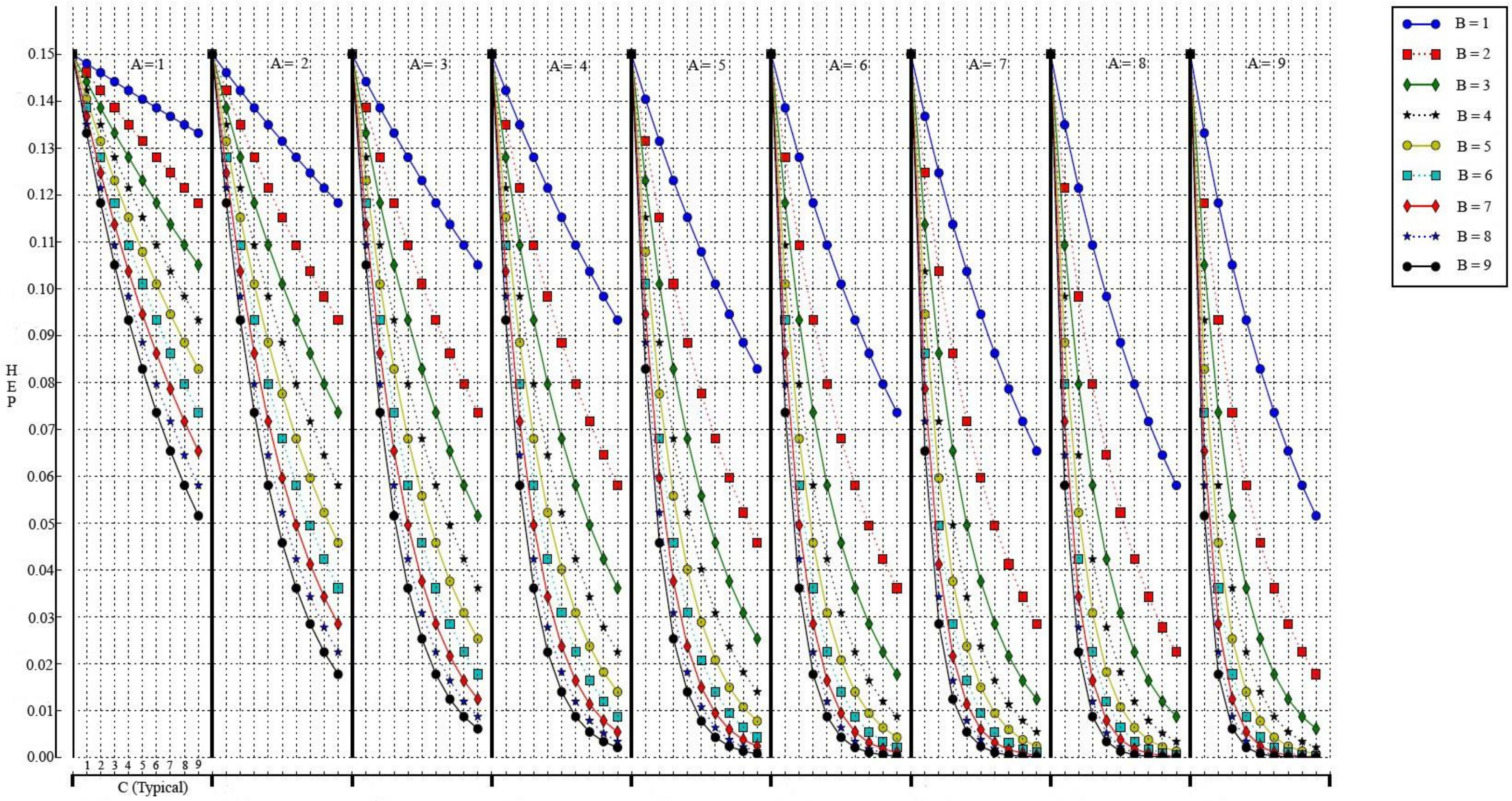


Figure 3-2: Human error likelihood monograph for maintenance activities in marine operations

As illustrated in Figure 3-2, the seafarer's training 'A' has nine sections from A=1 to A=9. For each section, the HEP value can be obtained as a function of seafarer's experience 'B' and fatigue 'C'. In order to estimate the HEP value, an example with three main steps is described below:

- First, specify the level of seafarer's training from 1 – 9 and identify the section of interest.
- Assign a value for seafarer's fatigue level C from 1 – 9 on an x-axis, and then draw a vertical line through the section of interest (i.e. A = 1 to A=9).
- In the final step the level of experience for an activity on board the ship is assigned. The intersection point between C and B represents the HEP value which can be read from a horizontal line on a y-axis.

For example, if for a given activity a seafarer's level of training is 8, level of experience is 4 and level of fatigue is 4, the HEP value of 0.025 can be estimated from the graph. Whenever (A, B and C) are zero, the HEP is 0.15. This is the maximum HEP estimated for this scenario and it is not necessary to demonstrate this point on a monograph.

This graph can allow the chief engineer or captain to make decisions in a particular situation based on operational and environmental factors. Application of this graph in instant decision making can support the internal safety programme to ensure compliance with approved maintenance and industrial safety practice. This monograph could also be used as guidance for ship owners, operators, masters and classification societies to better prepare and prioritise specific marine operations. It can also help ship management authorities to better schedule shifts for the operators, thus reducing the risk of fatigue. The monograph can be applied to container ships, bulk carriers, tankers, ferries, cruise ships, anchor handling and supply vessels for the offshore oil industry, salvage tugs, shipyards, and dockyard maintenance operations.

3.4 Application of the Error Assessment Monograph in Maintenance Activities: Case Study

In this section, an application of the developed monograph is demonstrated for the maintenance procedures of High Pressure (HP) fuel pump. Fuel injection is one of the most important systems for marine diesel engines. Diesel engine performance strongly depends on fuel injection systems. The main goal of the fuel system is to distribute the fuel to the cylinders of a diesel engine. HP fuel pumps play an important role in diesel fuel injection.

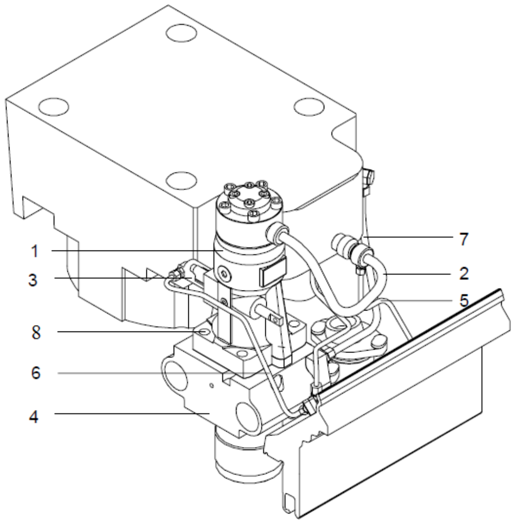


Figure 3-3: HP fuel pump (Service, 2001)

As shown in Figure 3-3, the HP fuel pump system contains fuel injectors and high pressure fuel lines where, (1) is the HP fuel pump connected with a protected HP line and (2) is connected to the injector. Each HP fuel pump is provided with an air operated stop cylinder (3) which brings the fuel rack to the zero position after controlling air admittance. The fuel oil supply and return manifolds are incorporated with the HP fuel pump brackets (4). There is also the fuel drainage line (5), the air removing line (6), a lubricating oil supply line for cooling the injector (7) and HP fuel pump nuts (8).

Table 3-1: HP fuel pump maintenance activities (Service, 2001)

Maintenance intervals of HP fuel pump						
Description		**Every (running hours)**				
		4000	8000	12000	24000	36000
1.0	**HP fuel pump maintenance activities**					
1.1	Inspection of fuel injectors, renewing nozzles and testing.					
1.2	Renewing inner parts of injector holders.					
1.3	Inspection of conical sealings and cavitation on inside of the HP fuel pipes.					
1.4	Renewing HP fuel pipes.					
1.5	Checking the fuel injection timing.					
1.6	Inspection of plunger, spring and spring at the bottom side of the HP fuel pump.					
1.7	Inspection and overhauling the HP fuel pumps, renewing pump elements and testing pump or renew complete pump.					

A breakdown of the activities for the maintenance procedure of the HP fuel pump is given in Table 3-1. The maintenance activities of the HP fuel pump in this study are selected according to previous accident investigation reports, expert opinion and engine manufacturer’s guidelines develop by Service (2001) .

Activity 1.1; Inspection of the fuel injector is very important to prevent engine fires. This inspection involves a testing of all the injectors for leaks in the injector body and output nozzle. Nozzles need to be renewed when the nozzle holes are clogged. Fuel injector testing includes spray pattern substantiation, consistency of spray pattern, testing the opening pressure, adjusting the opening pressure, checking the needle seat tightness and checking the needle spindle tightness. If there are deposits on the nozzle, the spray pattern can be severely affected. Even if the spray pattern is not affected by deposits, it is still possible for corrosion to cause variation in the flow rate.

Activity 1.2; Renewing the inner parts of the injector holder is also important in reducing the chance of nozzle clogging. The inner parts include the seals between the sealing surfaces in the cylinder head and the injector tip and the o-ring around the injector which prevents lube oil leaking in to the injector holder.

Activity 1.3; Inspection of conical seals and cavitation on the inside of the HP fuel pipe is equally important in reducing the chance of fuel leakage and ensuring the proper fuel flow rate.

Activity 1.4; Renewing the HP fuel pipes is necessary if fuel is found to be escaping at the leak off pipe which is caused by damaged seating cones.

Activity 1.5; Checking the fuel injection timing is likewise essential for marine engines. Injection timing plays a most significant role in determining engine performance, especially in pollutant emissions. Incorrect injection timing affects the combustion process and creates emissions such as Sulphur Oxide, Nitrogen Oxides and Carbon Dioxide. (Raeie et al., 2014) . Reduction of emissions is one of the main concerns of the International Maritime Organization, so it is essential to check the injection timing.

Activity 1.6; Inspection of the plunger, spring and spring at the bottom side of the HP fuel pump is similarly essential for the maintenance of marine engines. Too little spring pressure can cause the valve to babble on its seat and inject fuel into the cylinder too soon. This is caused by inadequate compression on the spring. Too high spring pressure can cause the valve to hammer on its seat and inject fuel into the cylinder too late. This is caused by too much compression on the spring. If the valve-seat is too deep in its seat, this causes a lagging of the fuel admission which results in late combustion and subsequent loss of power. In addition, the valve stem may be bent and this causes the valve to not seal on its seat and the valve stem will be tight in the nozzle body.

Activity 1.7; Overhauling a HP fuel pump depends on the results of renewing pump elements and pump testing or renewing the complete pump. This is another vital activity of marine engine maintenance. Overhauling is required when carbon is deposited on the nozzle or injector tips, when there are poor nozzle conditions, a broken spring, a need to clean the injector holder, a need to replace the plunger and barrel, when spray pattern needs testing, opening pressure needs testing, when there is tightness of valve seat, a need to delivery valve seat pressure test, or when there is a need to conduct a barrel seating face pressure test etc.

Table 3-2: Estimated HEPs for the maintenance procedures of HP fuel pump

Tasks		**Training 'A'** ([1]W=0.35)	**Experience 'B'** (W=0.40)	**Fatigue 'C'** (W=0.25)	**HEP**
1.1	Inspection of fuel injectors, renewing nozzles and testing.	6	6	5	1.40E-02
1.2	Renewing inner parts of injector holders.	8	7	9	1.90E-04
1.3	Inspection of conical seals and cavitation on the inside of the HP fuel pipes.	8	8	7	4.10E-04
1.4	Renewing HP fuel pipes.	8	8	8	1.75E-04
1.5	Checking the fuel injection timing	8	8	6	9.50E-04
1.6	Inspection plunger, spring and spring at the bottom side of the HP fuel pump.	8	9	6	5.0E-04
1.7	Inspection and overhauling all HP fuel pumps depending on results renewing pump elements and testing pump or renewing complete pump	6	6	7	5.40E-03

[1] W= Weighting

The weighting (W) of a PSF is important for estimating HEP which is assigned by the same experts who assessed the PSF. Weighting is estimated based on the importance of PSFs for the maintenance activities of HP fuel pump. For a given activity, the weighting of each PSF is normalised by dividing the sum of all PSF weighting for that activity, where the sum of all the PSF is 1. The mean PSFs weighting (mean of 3 experts) assigned by the experts is given in Table 3-2. Experience is the most important PSF among the three considered PSFs followed by training and fatigue respectively.

The rating of PSF is also equally important for estimating HEP. A PSF rating selected in this study range is from 0 to 9, where 0 is the minimum and 9 is the maximum value. The rating is determined for each of the 3 selected PSFs and seven activities of the maintenance procedures of HP fuel pump. The values for mean PSF ratings (mean of the 3 experts) are given in Table 3-2, which shows that experience has the highest and fatigue has the lowest PSF rating among the three considered PSFs for the seven activities. Table 3-2 also shows that rating and weighing data are rationally explainable and shows no significance biases arising from the expert panel that provided the data. Following the steps to read the monograph given in Figure 2, the HEP values for the maintenance activities of the HP fuel pump are estimated and given in Table 3-2. Considering Table 3-2, highest to lowest HEPs are I, VII, V, VI III, II and IV.

The highest HEP, I, is the inspection of fuel injectors, renewing nozzles and testing, which requires maintenance every 4000, 8000, 12000, 24000 and 36000 hours, which means that this activity requires the highest human interaction among the activities of the maintenance procedures for the HP fuel pump. Consequently, more human interaction may lead to more human error (Salvendy, 2012). As explained earlier, it also contains more tasks to be done by a maintenance engineer, some of which complex. As a result, it has the highest HEP value.

VII is the inspection and overhauling of all HP fuel pumps and requires maintenance only every 24000 hours. This means less human involvement is required than activity I. Although this activity has more tasks and some of them are quite complex, the human involvement in this activity is less than activity I, so it has a lower HEP than task I.

IV, The HP fuel pipes require maintenance every 24000 hours and need the same level of human involvement as activity VII, but it involves fewer tasks and also has fewer components. The tasks are also the most straightforward within the activities considered. Therefore it also has the lowest HEP value of all activities.

Although a HP fuel pump is considered to represent the application of the developed monograph in this study, however it can be applied to estimate HEP for the maintenance activities of any machinery in marine systems.

3.5 Conclusions

This study represents an approach to the development of a monograph for human error likelihood assessment in marine operations. Application of the developed monograph on the maintenance procedures of a HP fuel pump showed that the highest HEP value is 1.40E-02, which is for the inspection of fuel injectors, renewing nozzles and testing. The developed monograph could be a valuable tool to support the decision making process in a short period of time. This monograph enables chief engineers or captains to select the most suitable seafarers to complete maintenance tasks successfully based on operational and environmental conditions and thus decrease the risk of human error and accidents. It can also help them to be better prepared and to prioritise marine operation activities, which helps reduce the incidence of human error and accidents. The developed monograph for the assessment of human error likelihood for marine operations can help tackle the frequency of human error and serves to increase the overall safety of maintenance procedures in marine operations.

4. Development of a Human Reliability Assessment Technique for the Maintenance Procedures of Marine Operations

Abstract

Continuous monitoring and maintenance of assets is important for safe and reliable marine operations. On-board maintenance activities carried out by seafarers is often prone to error, leading to an accident. Marine environmental and operational conditions significantly affect human performance and influence seafarers to make un-intentional errors. International Maritime Organization (IMO) guidance recommends implementing Human Error Assessment and Reduction Technique (HEART) for assessing the effect of human error probability considering quantitative risk analysis of shipping operations. The conventional HEART is not specifically developed to apply to marine operations. Therefore, it is necessary to develop an operational specific methodology capturing unique features of marine environment and operations. In this study, by revising and modifying the HEART to assess and quantify the potential human errors in different marine environmental and operational conditions, a new methodology is developed. As a part of the developed methodology, the Error Producing Condition (EPC) and Error Influencing Factor (EIF) tables are refined and developed to reflect the particular conditions of marine environments for Human Error Probability (HEP) estimation. The EIF tables for both engine and deck departments are developed separately considering the answers to a questionnaire survey among experienced seafarers from around the world. The developed methodology is applied to the maintenance procedures of a marine engine exhaust turbocharger as a case study. Application of the developed methodology confirms that extreme weather, extreme workplace temperature, high ship motion, high level of noise and vibration, and work overload and stress increase the likelihood of human error as well as potential accidents. It is intended that application of this developed methodology in human factor risk assessment will assist to improve the safety and reliability of the current maintenance practices in marine operations.

Keywords: Human error probability, Maintenance procedures, Environmental and operational conditions, Marine operations.

4.1 Introduction

Human error is a dominant factor that affects the risk of accidents occurring during maintenance procedures in marine operations. Maintenance activities of marine operations are carried out by seafarers and are prone to errors. According to Marine Accident Investigation Branch (MAIB) UK, human error is considered one of the main reasons in the majority of maritime accidents (Tzannatos and Kokotos, 2009). American Bureau of Shipping (ABS) accident investigation report demonstrates that around 50% of maritime accidents are initiated by human errors (ABS, 2003). The advances in new technological components of the maritime industry increases the concern about the reliability of marine operations due to man-machine interface (Tzannatos, 2002). The main consequence of human error is incidents which can lead to accidents. There have been many incidents and accidents which have occurred around the globe during the maintenance activities over the past few decades (ABS, 2003; Islam et al., 2016a; TSB, 2013). Some of the reasons for human errors are: lack of training and experience, poor communication, inadequate system monitoring, failure to learn from previous accidents, human fatigue, stress, work memory and appreciation by higher management. Additionally, both internal (on-board ship) and external (ocean) factors influence seafarers' performance during the maintenance procedures of marine operations. Weather conditions, workplace temperature, ship motion, noise and vibration, over and under workload and stress are some examples of these factors (Hetherington et al., 2006; Li and Ng, 2002; Sillitoe et al., 2010; Stevens and Parsons, 2002; Xhelilaj and Lapa, 2010).

Weather conditions, which include wind speed and direction, waves and swell (significant and maximum height, mean or peak period and direction), rain, snow, storm surge, and barometric pressure, significantly affect seafarers' maintenance activities in marine operations. It is often hostile in the marine environment. An extreme weather condition has a major impact on seafarers' marine operation activities. Tupper (2013) reported that from 1993 to 1997, over 582 ships went missing, 33 % of these were due to extreme weather conditions of the sea. Moreover, around 1200 seafarers go missing every year because of extreme weather conditions at sea (Tupper, 2013). Historically, disastrous marine accidents have occurred in different countries due to these extreme weather conditions. For example, an unexpected storm in the Black Sea led to the sinking of thirty British and French warships in the Crimean War in 1854. Another example of a disaster caused by an extreme weather condition is the sinking of a large passenger ferry in Estonia due to a storm in the Baltic Sea in 1994. In this disaster, 852 passengers and seafarers lost their lives (Langewiesche, 2010). In an extreme weather condition, a ship can be at risk even if it is at anchor. The damage to the Indonesian bulk carrier Bogasari Dua and the Panamanian bulk carrier Midas are examples of such a condition. Both of these ships were damaged at anchor due to an extreme weather condition (Gilbert, 1998). Often rogue waves are one of the significant safety hazards for marine operations. Due to rogue waves, more than 200 ships have been sunk over the past 20 years (Butcher, 2006). Wind speed and wave height are the most important factors of the ocean environment which have affected human performance (Ross, 2009). Extreme weather generates ship motion, noise and vibration, as well as increases the workload and stress. This significantly decreases the seafarers' performance and influences their activities, in turn leading to human error (Arslan and Er, 2008; Berg, 2013; Kristiansen, 2013).

Workplace temperature is another important factors lowering seafarers' performance in marine operations. Extreme temperature conditions (hot or cold) can negatively affect seafarers' performance in many ways. It may cause fatigue and decrease their ability to concentrate on the task at hand. High temperature may cause a seafarer's body temperature to rise, which could lead to serious health issues including heat stroke. On the other hand, low ambient temperature may decrease body temperature, leading to health and operational consequences (Hancock et al., 2007). Continuous heat stress may lead to loss of body fluid which in turn decreases performance, particularly endurance. It may also harm mental and psychomotor functions, ultimately affecting human performance. The amount of time a person can suffer will be decreased by enhancing metabolic rates (Noroozi et al., 2014a). Mental abilities and perception are also badly affected by extremely cold temperature. Rate of the perceptual error is increased due to decrease in operational temperature. Physical distractors (noise or moving environments) along with operations in cold temperatures impact on the quality of perception, memory, and reasoning. Therefore, chance of error increases during the decision making process (Noroozi et al., 2014a). Cold weather also significantly decreases the physical performance and negatively impacts on task completion. Decreasing strength, mobility and balance can be taken into account as direct deficits of physical performance. Cold weather ultimately affects physical performance due to decrease in flexibility and incapability to identify external elements. Parsons (2014) stated that if a seafarer is outfitted in Arctic clothing due to extremely cold weather, a substantial performance decrement is observed when compared to the normal condition. Reduction of perception and misunderstanding can be the cause of extreme cold stress. Several other researchers including Hoffman (2001); Pilcher et al. (2002); Van Orden et al. (1996); Wright et al. (2002) believed that human performance in 22°C ambient temperature may lead to less chances of error when compared to human performance in temperatures below 5°C.

Ship motion is another reason of seafarers' performance reduction and influences seafarers to make unintentional errors. The usual cause of motion is the interaction between a ship, its appendages and the sea. Wind acting on a person may also cause motion stability posture. The most important factor affecting a ship's motion is clearly the ship size, particularly its length in relation to the sea conditions encountered (Bertram and Schneekluth, 1998; Lewis, 1988). Smaller ships have a higher chance of roll and pitch motion than the larger ships (Faltinsen, 1993; Lewis, 1988). Heave is a key motion element for sea sickness. Likewise, roll and pitch motions also contribute, particularly the further away from the centre of gravity. However, latest experimental studies of ship's motion demonstrate that, roll and pitch motion is perceived about 50% of total motion sickness. Although the sensitivity to motion sickness differs for each individual and can develop slowly or quickly (Wertheim, 1998). Sometime due to the excessive ship motion, seafarers feel uncomfortable. It degrades their performance mentally and physically, as well as making them less efficient, creating task difficulty and sometimes even the impossibility to conduct the task (Tupper, 2013). A study by Colwell (2005) confirmed that seasickness among experienced seafarers is lower than inexperienced seafarers, although the ship's motion can still cause Motion Induced Fatigue (MIF) or interrupt challenging operations such as maintenance activities on board ship. Seafarers may become mentally depressed due to motion sickness. Experienced seafarers usually adapt more rapidly than those less experienced. It has also been found that seafarers performance is significantly affected even with mild motion sickness and the degradation becomes more noticeable as motion sickness increases (Bos, 2004).

Noise and vibration also affect seafarers' performance and increase the chance of human errors. There are many sources of noise and vibration present in a ship such as prime movers (typically diesel engines), shaft-line dynamics, slamming phenomena, water flow along the hull and wind (Carlton and Vlasic, 2006). Noise and vibration can degrade stamina and alertness, affecting both productivity and the safety of operations. Noise and vibration can also lead to strain and fatigue. They are also responsible for the seafarers' hearing damage, sleep disturbance, irritability and decreased performance. Researchers such as; Cohen and Weinstein (1981); Fahy and Walker (1998); Stansfeld and Matheson (2003) believed that noise and vibration have a significance impact on human performance which initiates the lack of attentiveness, fatigue, annoyance, hearing hazards etc. Persistent exposure to noise causes fatigue and confusion. This may significantly affects the maintenance procedures of on board the ship (Ross, 2009).

Finally, workload and stress also impact the seafarers' activities and cause human errors. When the seafarers' workload increases, this performance generally decreases. This performance decrement could be responsible for an increase in unintentional errors or longer target detection times. However, a performance decrement does not always occur because individuals can devise strategies that allow them to maintain current performance levels as workload increases. Encountering work overload is a very common problem in seafarers. It is initiated by too much effort to come across the demand being placed upon them. Similar to overload work, underload can also be a problem due to the low level of exertion and stimulation. Extreme overload and underload both equally lead to human errors. Based on the experiment, the best performance occurs in a mid-range of arousal or stress (Yerkes and Dodson, 1968). If the seafarers are not focused or are bored, this may lead to errors. After a long period of time, workload may lead to sleep loss and fatigue. Fatigue is an illustration of a chronological unproductive team response in a transitional workload situation. The Exxon Valdez accident is one of the best examples of this type of situation (Wickens and Huey, 1993). Overload can be increased by lack of seafarers' experience, lack of sleep, insufficient personnel, and perceived danger, time constraints, task difficulty and heat, all of which distract and force the seafarers to focus more closely on the task at hand (Embrey et al., 2006). In these circumstances, it is very hard for seafarers to stay focussed on the maintenance task (Embrey et al., 2006).

For consistent marine operations, maintenance is essential. Maintenance reduces the number of accidents, improves the efficiency of, and extends the life of equipment, prevents large repair bills and unexpected break downs, saves time, and improves the safety and reliability of operations. The type of maintenance required is dependent on the equipment design, the reliability of the equipment and the number of chances available to access the equipment. Most of the maintenance activities of marine operations are conducted under challenging working conditions. Shipping is a safety critical industry and maintenance activities are carried out by seafarers who are liable to make errors. Needless to say human error within the maintenance activities of marine operations is unavoidable.

In order to improve the performance of human–machine systems and decrease the likelihood of human errors, it is necessary to evaluate and quantify human performance in maintenance procedures. Many researchers Abbassi et al. (2015); Deacon et al. (2013); Dhillon (1987); DiMattia (2004); Islam et al. (2016); Noroozi et al. (2013) applied the human reliability assessment concepts to various industries. DiMattia (2004) applied this concept for investigating the human performance in offshore platform musters. Deacon et al. (2013) applied a human reliability assessment technique for the analysis of human performance in offshore evacuations systems. Noroozi et al. (2013) investigated the human reliability in pre- and post-maintenance procedures of offshore oil and gas facilities and Islam et al. (2016a) quantified the human errors during maintenance procedures of marine engines. The above mentioned studies are proven evidence of the importance of quantifying human errors in risk assessment of different engineering operations. Estimating and quantifying human error assists in decreasing the risk of human errors in maintenance procedures and eventually contributes to reducing shipping accidents.

Some of the most common approaches of human error likelihood assessment are: Technique for Human Error Rate Prediction (THERP), Success Likelihood Index Method (SLIM) and Human Error Assessment and Reduction Technique (HEART) (Kirwan, 1994). THERP is the most common approach for quantitative human error assessment but the usefulness of this approach is limited to error reduction. Further, it does not offer adequate guidance for demonstrating the effects of Error Producing Conditions (EPC) and scenario development (Jae and Park, 1995). SLIM is one of the known approaches for quantitative human error assessment based on expert judgment. This method requires to obtain Performance Shaping Factors (PSFs) considering an expert judgement which is associated with different uncertainty and affected the final results. While HEART is easy to grasp, fast and trustworthy (Casamirra, 2009). Though, the HEART is a reliable approach for comparing HEP it is based on the degree of error recovery. Noroozi et al. (2014c) applied HEART to determine the HEPs for the maintenance procedures of a pump. Previous applications confirm HEART has general applicability and can be applied in maintenance procedures of marine and offshore operations (Noroozi et al., 2014c). Furthermore, a recent International Maritime Organization IMO (2002) guideline proposed HEART for the human error probability assessment in the shipping industry.

Conventional HEART approach was developed by Williams (1986) for use in overall engineering systems (Kirwan, 1996). This approach requires revising in order to applicable for the maintenance procedures of marine operations for the HEP assessment. It is still challenging to model human error for the shipping industry and it thus deserves further research. In this study, the HEART methodology is revised to make it particularly applicable for the maintenance procedures of marine operations in different environmental and operational conditions. The objective of the current study is to develop a particular technique applicable for the maintenance procedures of marine operations. The proposed methodology will assist the shipping industry in more precisely investigating the probabilities of human error and the associated risk. Overall, this study will help in improving the safety and reliability of the maintenance procedures on board ships.

4.2 Development of the methodology

In human reliability assessment calculations, to evaluate the HEPs generally HEART methodology is applied, however, marine environmental and operational conditions are different from other engineering operations. As a result, refinement of the current methodology is required for assessment of the HEPs for the maintenance procedures of marine operations. The developed methodology includes three steps to estimate the HEPs for the maintenance procedures of marine activities, as illustrated in Figure 4-1.

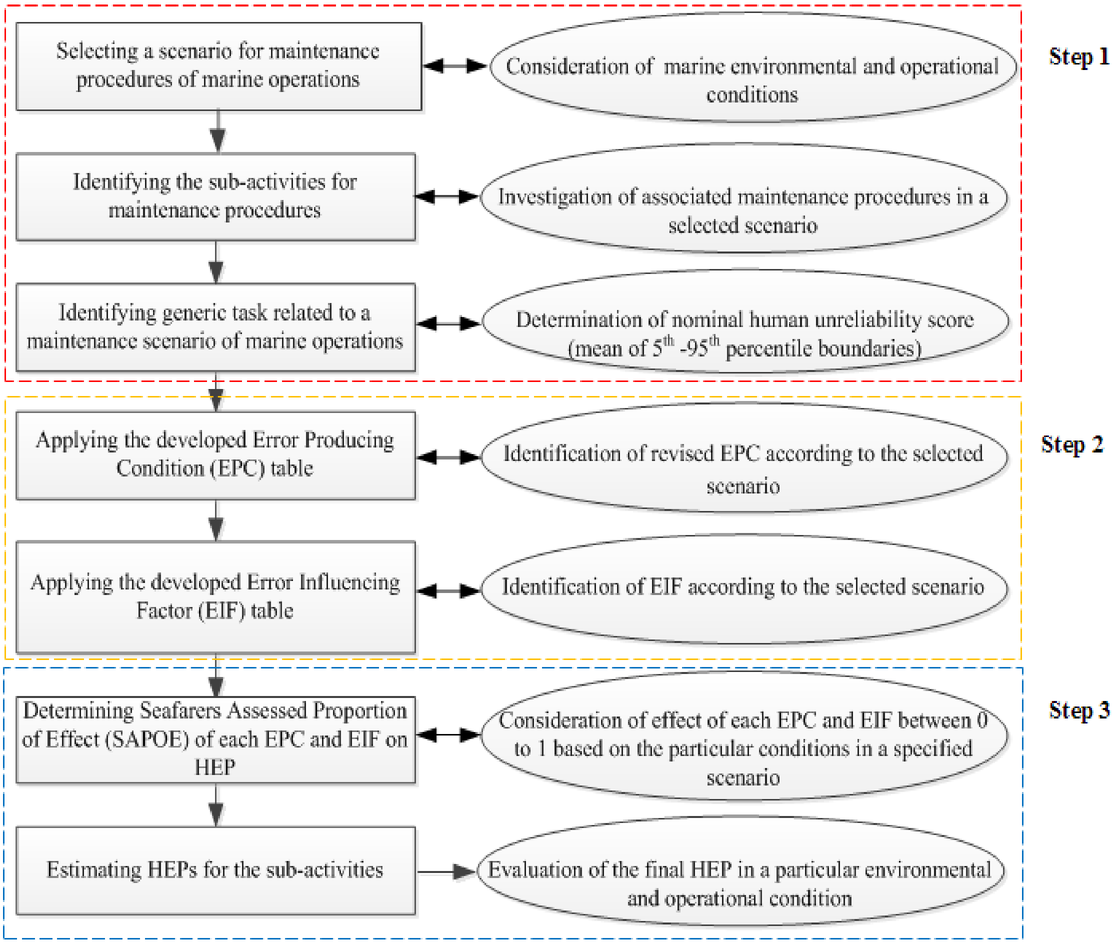


Figure 4-1: Developed methodology for estimating the HEP for maintenance procedures of marine operations

In the first step, scenario selection, identification of the sub-activities and generic task for the maintenance procedures in marine operations is necessary. To select a particular scenario an impact of marine environmental and operational conditions on operation is necessary. Likewise, different steps considered conducting each activity or sub-activities should be identified. After identifying the sub-activities, it is required to identify generic task related to the maintenance scenario in order determine nominal human unreliability score. Generic task is a nature of seafarers' activity or performance and it is classified as a complex task, routine task etc. In the developed technique, human unreliability considers mean of the 5th to 95th percentile boundaries for a particular sub-activity which is adopted from (Williams, 1986). The generic task category and the nominal human unreliability score of each category for the maintenance procedures of marine operations are given in Table 4-1. Nominal human unreliability is a scale /label of the possible error which make human performance unreliable.

Table 4-1: HEART generic categories (Williams, 1986)

Generic task	**Task type**	**Proposed nominal human unreliability (mean of 5th to 95th percentile boundaries)**
Routine, highly-practised, rapid task involving relatively low level of skill	E	0.02
Restore or shift a system to original or new state following procedures, with some checking	F	0.003
Completely familiar, well-designed, highly practised, routine task occurring several times per hour, highly trained and experienced person	G	0.0004
Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system stage	H	0.00002

In the second step, the developed EPCs from Table 4-2 need to be applied to identify multiplier of nominal probability for the maintenance procedures in marine operations. EPCs are evident in the scenario which has a negative influence on seafarers' performance. Also, multiplier of nominal probability is an amount of EPC by which human unreliability increases. The development of EPC for maintenance procedures of marine operations is discussed in the next section. There are 37 EPCs in the developed tables that influence HEP. Selection of proper EPC among the 37 is usually based on the scenario for the sub-activity under consideration. Each EPC has a multiplier of nominal probability which should be inserted in the Equation 1 as EPC representative. Furthermore, it is also necessary to apply Error Influencing Factors (EIFs) to estimate the HEPs accurately as the EPC table does not cover all aspects of marine operations. EIFs are the critical environmental and operational factors that influence seafarers to make an error. The development of EIF table for maintenance procedures of marine operations is discussed in section 4.3.2. The EIFs table is developed using the questionnaire survey mentioned in Table 4-3. Also, importance of the factors from the survey data is presented in Table 4-4 and proportional effect of each individual factor is shown in Table 4-5 and finally developed EIF table illustrated in Table 4-6. Application of the EIFs from Table 4-6 require identifying multiplier of nominal probability for the maintenance procedures in marine operations. There are 13 EIFs in the developed table which have an influence on HEP. Selection of appropriate EIF among the 13 possibilities is usually based on selecting a scenario for the sub-activity under consideration. Each EIF has multiplier of nominal probability which should be inserted in the Equation 4-1 as EIF representative.

Finally in step 3, it is necessary to assign Seafarers Assessed Proportion of Effect (SAPOE) and estimate overall HEP. SAPOE includes EPC and EIF effect on seafarers' performance. SAPOE is weighted for each selected EPC and EIF based on its importance by the experts. Each EPC and EIF is individually weighted from 0 to 1 according to the analyst judgement on how much it influences the overall unreliability of each activity.

$$\text{Assessed effect} = (\text{Maximum effect} - 1) \times \text{SAPOE} + 1 \qquad \textbf{[4-1]}$$

Equation 4-1 is used to estimate the effect of each EPC, EIF and its relevant SAPOE on nominal human unreliability. The HEP of each sub-activity is estimated by multiplying the selected nominal human unreliability with nominal value of SAPOE related to each EPC and EIF.

4.3 Development of EPC and EIF tables

To estimate HEP accurately for the maintenance procedures of marine operations EPC and EIF tables are developed in this study. This helps to consider the effect of particular environmental and operational conditions on seafarers' activities during maintenance. These tables are developed to capture unique features of marine conditions. Details of the development procedures of EPC and EIF tables are described in sections 4.3.1 and 4.3.2.

4.3.1 EPC table development

The EPC table for the maintenance procedures of marine operations, is developed by revising the conventional EPC table of HEART. This is conducted by consulting with a number of experienced seafarers both in the deck and the engine department. The selected seafarers have more than 5 years of experience in various types of maintenance activities on board ships. The qualitative representation of the conventional EPC table is modified to epitomize seafarers' error assessment in marine operations. The revised table is developed specifically for the maintenance activities on board ship. As shown in Table 4-2, the total 37 EPCs are considered for the maintenance procedures of marine operations. The multiplier of nominal probability value is adopted from Williams (1986) and fitted to the relevant EPC for marine operations. Among the 37 considered EPCs for maintenance procedures of marine operations, unfamiliarity with the ships systems and equipment has the highest multiplier of nominal probability. This confirms that the lack of familiarity of the seafarers with ships systems and equipment is the highest contributor to making an error during maintenance activities in marine operations. Previous investigations by (Håvold, 2010; Hetherington et al., 2006) show that seafarers' familiarity with the ship's system and equipment is very important in order to perform well during maintenance activities in marine operations. On the other hand, the age of seafarers performing physically demanding maintenance tasks has the lowest multiplier of nominal probability, showing a lower influence in making an error during the maintenance activities in marine operations. Likewise, as much as the EPC's multiplier of nominal probability is higher, chances of making an error is also higher. The developed EPC table for the maintenance procedures in marine operations is demonstrated in Table 4-2.

Table 4-2: Developed EPC table for the maintenance procedures of marine operations

	Error-Producing Condition	Multiplier of nominal probability amount
1	Lack of familiarity with ship's systems and equipment but does not occur frequently	17
2	Shortage of time available for error diagnosis and repair within the system	11
3	Not following easily accessible information such as maintenance and troubleshooting manual for the tasks	9.0
4	Mistakes in maintenance manuals or out of date manuals	8.0
5	A discrepancy between the seafarers practise and that of the ship designer	8.0
6	No obvious means of reversing an unintentional action in a maintenance task	8.0
7	An overload of information for the maintenance	6.0
8	Apply a modified technique during maintenance which may be not be current practice	6.0
9	Seafarers need to transfer accurate knowledge from task to task without any loss	5.5
10	Uncertainty in the required performance standards of seafarers set by the IMO	5.0
11	A difference between apparent and real risk of the maintenance tasks	4.0

12	Poor, unclear or improper information written in the ship's maintenance logbook provided by the previous seafarers who have already finished their shift	4.0
13	Confirmation of system's response for intended action not direct or timely	3.0
14	Inexperienced seafarers (i.e. newly qualified, or newly joined crew)	3.0
15	A poor quality of information conveyed by usual procedures and crews on-board	3.0
16	A poor or no quality check by the supervisor	3.0
17	A conflict between short and long-term objectives of the maintenance tasks	2.5
18	Inadequate information for accuracy checks for the maintenance tasks	2.5
19	A knowledge and skill gap between the educational successes of a seafarer and the requirements of the maintenance task	2.0
20	A guidance by the senior seafarer/supervisor for using difficult procedure for the maintenance	2.0
21	Seafarers have less opportunity to exercise mind and body outside the immediate limitations of the maintenance work	1.8
22	Faulty maintenance equipment, tools and spare parts	1.6
23	A need to make decisions that are beyond the level of an experience seafarer	1.6
24	Lack of proper distribution of maintenance tasks and responsibility among the seafarers	1.6
25	Improper way to keep track of progress during a maintenance activity	1.4
26	A danger (i.e. concentration limits of toxic chemical) that can exceed physical capabilities of seafarers	1.4
27	Less importance given to the particular maintenance task	1.4
28	Seafarers high-level of emotional stress (feeling lonely or home sick) because of being away from home and family	1.3

29	Symptom of ill health among seafarers	1.2
30	Low morale by the crew at maintenance work	1.2
31	Contradiction in the meaning of displays and procedures of maintenance task	1.2
32	Poor lighting in which the maintenance work is being performed	1.15
33	Persistent inoperativeness or very repetitious cycling of low mental workload of maintenance tasks	×1.1 for first half hour ×1.05 for each hour thereafter
34	Interruption of seafarers standard work-sleep cycles set by the regulators	1.1
35	Maintenance task pacing due to the disturbance of other colleagues	1.06
36	Additional or lack of team members than those required, to satisfactorily perform maintenance	× 1.03 per additional seafarers
37	Age of seafarers performing physically demanding maintenance tasks	1.02

4.3.2 EIF table development

EPCs do not cover all aspects of marine environmental and operational conditions such as weather, workplace temperature, type of ship motion, level of noise and vibration and range of workload and stress. These aspects have significant impact on reducing seafarers' performance which leads to error during on-board maintenance activities. As a result, the EIF table is developed in this study to supplement the EPC table considering particular marine environmental and operational conditions to estimate HEP more accurately. The ocean environment is concerned as it presents significant risks to the safe marine operations due to waves, wind and possibly ice. Similarly, considering ambient temperatures is also important for safe marine activities.

The internal environmental factors (i.e. - noise/poor lighting system in the engine room) along with sea environmental conditions determine the wellbeing of seafarers. Therefore, both environmental and operational conditions are required to be considered to develop EIF table. There are four different steps in order to develop the EIF table, as demonstrated in Figure 4-2. These steps include selection of the most important marine environmental and operational factors by considering previous literature and expert opinions. The expert opinions on these factors have been received and analysed using the questionnaire. The individual steps followed to develop the EIF table are discussed in more detail in the following sections.

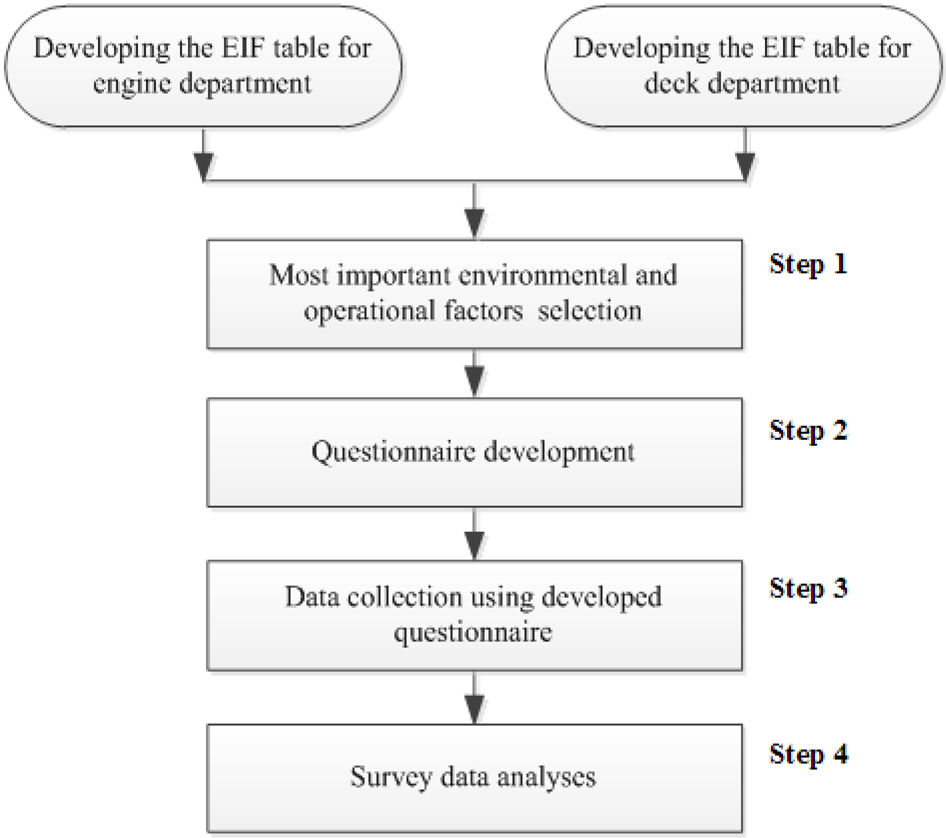


Figure 4-2: Development of EIF table

4.3.2.1 The most important factors selection (Step-1)

There are five different factors considered in this study. These five factors are considered according to previous studies by Baitis et al. (1995); Batra and Borg (2005); Bos and Bles, 2000; Colwell (2005); Driskell and Salas (2013) . Moreover, seafarers’ opinions are taken into account in order to select the most effective factors. Each seafarer has more than five years' experience in the maintenance activities on board ship. The considered factors are: weather, workplace temperature, ship motion (roll and pitch), noise and vibration, and workload and stress. It is believed that these are the most important environmental and operational factors affecting the overall probability of human errors. The considered factors may influence each other, however, in this study only individual effect of the factor on seafarers' performance is taken into account. For example, weather condition may have an influence on the ship motion, however, weather and ship motion are considered an individual factor in this assessment. This was clarified and shared with the experts in the developed questionnaire.

4.3.2.2 Questionnaire development (Step-2)

A questionnaire was developed to determine the EIF considering particular marine environmental and operational conditions and their effect on seafarers' performance during maintenance procedures. Prior to conducting the survey, it was also reviewed by the experienced seafarers

The factors that affect the seafarers' performance in engine and deck departments are different. The seafarers in the deck department mostly performed maintenance activities in the weather deck. Therefore, the environmental factors (including weather) may have more impact on seafarers' performance than those performing the maintenance activities in the engine room. Moreover, some of the considered factors such as noise may affect seafarers during the maintenance activities in the engine room more than on the weather deck. This is because the engine room is normally placed in a confined area and the level of noise is reflected and increased. As shown in Table 4-3 there are two sections in the questionnaire. Section "A" is for defining the importance of the factors and section "B" is to estimate the proportional effect of an individual factor in order to develop EIF table. There are seven questions in total in the questionnaire. Question 1 (in section "A") is used to investigate the importance of influencing factors affecting the seafarers' performance.

Questions 2 to 7 (in section "B") are developed to define the Seafarers' Assessed Proportion of Effect (SAPOE). Question 2 is developed according to the North Atlantic Treaty Organization sea state definitions adopted from Ross (2009). Sea state 0-3, wave height 0-1.25 m and wind speed 0-16 KT is classified as a *normal* weather condition. Likewise sea state 4-6, wave height 1.25-6 m and wind speed 17-47 KT is classified as *moderate* weather condition. Finally, sea state 7-9, wave height of 6-14 m and wind speed of 48-63 KT or more is classified as *extreme* weather conditions. Seafarers normally follow the sea state, wave height and wind speed data to determine the severity of the sea conditions for making the decision for the voyage and other operational matters.

Question 3 is developed considering temperature around 20°C as *normal* for human performance reported by previous researchers (Eraut, 2007; Pilcher et al., 2002). On the other hand, ambient temperatures higher or lower than a human being's comfort zone are considered as *extreme* temperature, 32.2°C and above is hot, and 10°C and below is cold (Pilcher et al., 2002).

Question 4 is developed according to the motion limits for safe and effective seafarers performance which is adopted from Ross (2009). *Low* ship motion is categorized at <4º roll angle and <1.5º pitch angle. On the other hand, 4-10º roll angle and 1.5-5º pitch angle is categorized as *medium* ship motion. Finally, >10º roll angle and >5º pitch angle is categorized as *high* ship motion.

Question 5 is developed according to the range of noise and vibration level and adopted from Turan et al. (2011). Noise level of 110 dB (A) or less and vibration level less than 1 Root Mean Square (RMS) is considered as *low*. However, the noise level higher than 110 dB (A) and the vibration level more than 1 RMS is considered as *high*.

Question 6 is developed to show how extreme work overload and underload may lead to human error. Considering previous research (Ross, 2009), workload and stress is categorized as mid-range underload and overload. A low work load within an available time together with a seafarers' high skill level for a very low-level task, is categorized as an underload. Similarly, too much work to be done in a limited time is categorized as overload.

Finally, question 7 is an open-ended question and was developed to realize the quality of the questionnaire and to allow any other effective factors which have not been considered in this study. The developed questionnaire is explained in Table 4-3. The five point Likert, scale based on ratings 1-5, is applicable for each specific question. Rating 1 has the lowest and 5 has the highest effect on seafarers' subsequent performance.

Table 4-3: Questionnaire shared with experts for developing the EIF table

Please indicate, where do you perform maintenance operations on board ship?		(✓)
	Deck	
	Engine room	
Please write your years of experience		
Please write the duration of your voyage (while participating in this survey)		

Section ("A") Question 1		Rating 1-5
How important are the following influencing factors in decreasing seafarer's performance during maintenance operations on ships (Please rate it)	Weather	
	Workplace temperature	
	Ship Motion (Roll and Pitch)	
	Noise and Vibration	
	Workload and Stress	

Section ("B") Question 2		Rating 1-5
How important are the following classified weather conditions in decreasing seafarer's performance during maintenance operations on ships? (Please rate it)	Normal	
	Moderate	
	Extreme	

Section (“B”) Question 3		Rating 1-5
How important are the following work place temperatures in decreasing seafarer’s performance during maintenance operations on ships?	Normal	
	Extreme temperature (cold or hot)	

Section (“B”) Question 4		Rating 1-5
How important are the following levels of ship motion (roll and pitch) in decreasing seafarer’s performance during maintenance operations on ships? (Please rate it)	Low	
	Medium	
	High	

Section (“B”) Question 5		Rating 1-5
How important are the following types of noise and vibration in decreasing seafarer’s performance during maintenance operations on ships? (Please rate it)	Normal	
	Extreme temperature (cold or hot)	

Section (“B”) Question 6		Rating 1-5
How important are the following workload and stress factors in decreasing seafarer’s performance during maintenance operations on ships? (Please rate it)	Mid–range	
	Underload	
	Overload	

Section (“B”) Question 7	
Please make any comments (if you want) regarding this research. Please write in the box.	

4.3.2.3 *Data collection using developed questionnaire (Step-3)*

A Survey Monkey link was created in order to conduct and facilitate the questionnaire survey. Prior to sending the questionnaire to seafarers, a human research ethics approval was obtained from the University of Tasmania's human research ethics committee. The Survey Monkey link was sent around the world by email to a total of 400 experienced seafarers, 200 in each department (i.e. engine and deck). A total of 121 responses were received from the engine department and 114 responses from the deck department. Response rates therefore in engine and deck departments is 60.5% and 57% respectively.

To statistically justify the accuracy of the results the required sample size is calculated using Equation 4-2.

$$\text{Initial sample size } n = \frac{Z^2\ P(1-P)}{e^2} \qquad \textbf{[4-2]}$$

$$= \frac{(1.96)^2\ (0.50)(0.50)}{(0.10)^2} = 96$$

In Equation 4-2, margin of error is *e*; level of confidence 95% in the survey estimates Z, and P is the level of satisfaction assumed to be 0.5 as the correct number of seafarers around the world is unknown. The initial sample size calculation in this study needs to be considered as 96. This justifies the statistical accuracy of the results received in the assessment.

4.3.2.4 *Data analysis (Step-4)*

Shown in Table 4-4 is the seafarers' survey data received from Engine Department (ED) and Deck Department (DD). Mean value has been considered from both department's survey data for all five considered factors and is presented in Table 4-4.

Table 4-4: Mean value of the factor's importance for ED and DD

Serial number	**Factors**	**Mean Value**		**Standard deviation**	
		ED	**DD**	**ED**	**DD**
1	Weather	3.86	3.89	1.01	0.90

2	Workplace Temperature	3.80	3.32	0.98	0.89
3	Ship Motion (Roll and Pitch)	3.97	3.62	0.83	0.98
4	Noise and Vibration	3.46	3.13	1.04	1.10
5	Workload and Stress	4.21	3.95	0.93	0.89

Figure 2-1 illustrates the comparison of the factor's importance between ED and DD seafarers which slightly differ between these two departments. Importance factor of the DDs is comparatively less than the EDs, apart from the factor of weather. This is because the DD seafarers are require to perform maintenance activities on the weather deck of the ship which is an open place and weather conditions can therefore directly affect their performance. However, for the ED, maintenance activities are performed in the engine room which is normally at the bottom of the ship and is a confined area. In both of these departments, workload and stress factor has the highest importance. Workload and stress increases due to commercial pressure or overloaded and underload tasks which affect seafarers performance (Embrey et al., 2006; Wickens and Huey, 1993). Moreover, the importance of noise in ED is higher than DD. The noise effect, during the maintenance activities in the engine room, is more than the maintenance activities on the weather deck as noise is reflected in the engine room due to the enclosed space (Lundh et al., 2011).

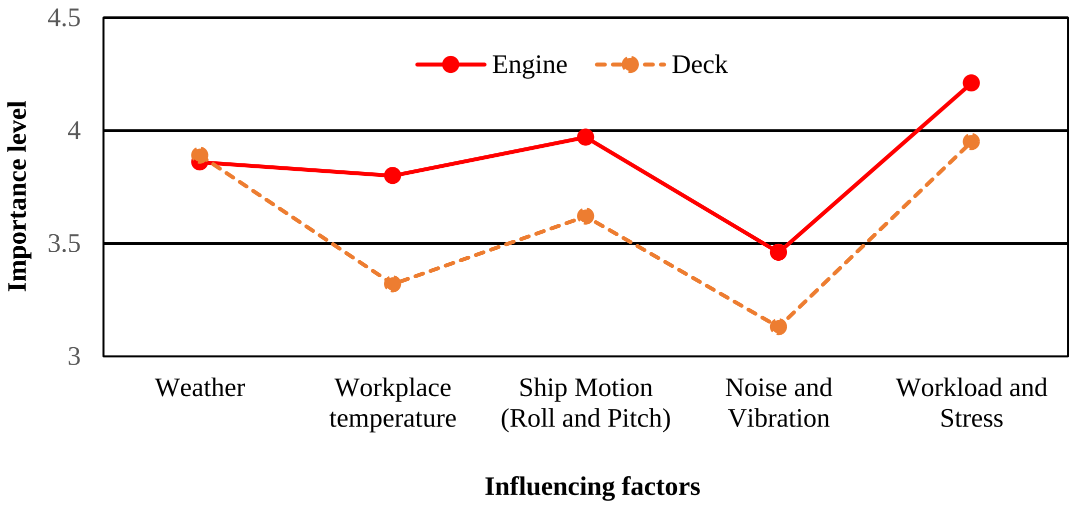


Figure 4-3: Comparison between ED and DD of the factor's importance

After estimating the importance of each factor, it is required to estimate proportional effect of each individual factor in order to develop the EIF table. The proportional effect of each individual factor is estimated from the responses received from section "B". These proportional effects of each individual factor for ED and DD are shown in Figure 4-5.

Table 4-5: Proportional effect of an individual factor for ED and DD

Serial number	Factors		Proportional effect of an individual factor	
			ED	DD
1	Weather	Normal	0.31	0.31
		Moderate	0.59	0.57
		Extreme	0.89	0.85
2	Workplace Temperature	Normal	0.32	0.33
		Extreme	0.77	0.79
3	Ship Motion (Roll and Pitch)	Low	0.32	0.31
		Medium	0.61	0.58
		High	0.87	0.84
4	Noise and Vibration	Low	0.35	0.36

		High	0.74	0.72
5	Workload and Stress	Mid-range	0.37	0.38
		Underload	0.52	0.53
		Overload	0.88	0.87

After achieving the proportional effect of an individual factor, the EIF table is developed by multiplying it with the importance of the factors and normalising the results by dividing the final outcome of the value received in the normal, low and mid-range conditions. The developed EIF table for the maintenance procedures of ED and DD is presented in Table 4-6. The data analysis received from this survey confirms that marine environmental and operational conditions have substantial effects in creating human error during maintenance activities. Therefore, it is vital to develop the EIF table along with EPC table to estimate the HEP accurately during the maintenance activities.

Table 4-6: EIF assessment for engine and deck departments

EIF		**Multiplier of nominal probability amount**	
		ED	**DD**
1	Normal weather condition	× 1.00	× 1.00
2	Moderate weather condition	× 1.90	× 1.83
3	Extreme weather condition	× 2.87	× 2.73
4	Normal workplace temperature	× 1.00	× 1.00
5	Extreme workplace temperature	× 2.40	× 2.39
6	Low ship motion	× 1.00	× 1.00
7	Medium ship motion	× 1.90	× 1.87
8	High ship motion	× 2.71	× 2.70
9	Low noise and vibration level	× 1.00	× 1.00

10	High noise and vibration level	× 2.11	×2.00
11	Work –range and stress	× 1.00	× 1.00
12	Work underload and stress	× 1.40	× 1.39
13	Work overload and stress	× 2.37	× 2.29

4.4 Application of the Methodology: Case Study

The developed methodology is applied for the maintenance procedures of a marine engine exhaust gas turbocharger to estimate the HEP. A turbocharger is one of the important devices in marine engines. It consists of a turbine and a compressor built together as a single unit. The turbocharger is driven by an exhaust gas and helps to pre-heat the air to the engine cylinder to a considerably higher temperature than the atmospheric pressure. Furthermore, it utilises energy in the exhaust gasses and improves the engine's efficiency. To get the desired output from the turbocharger, maintenance is a very important task.

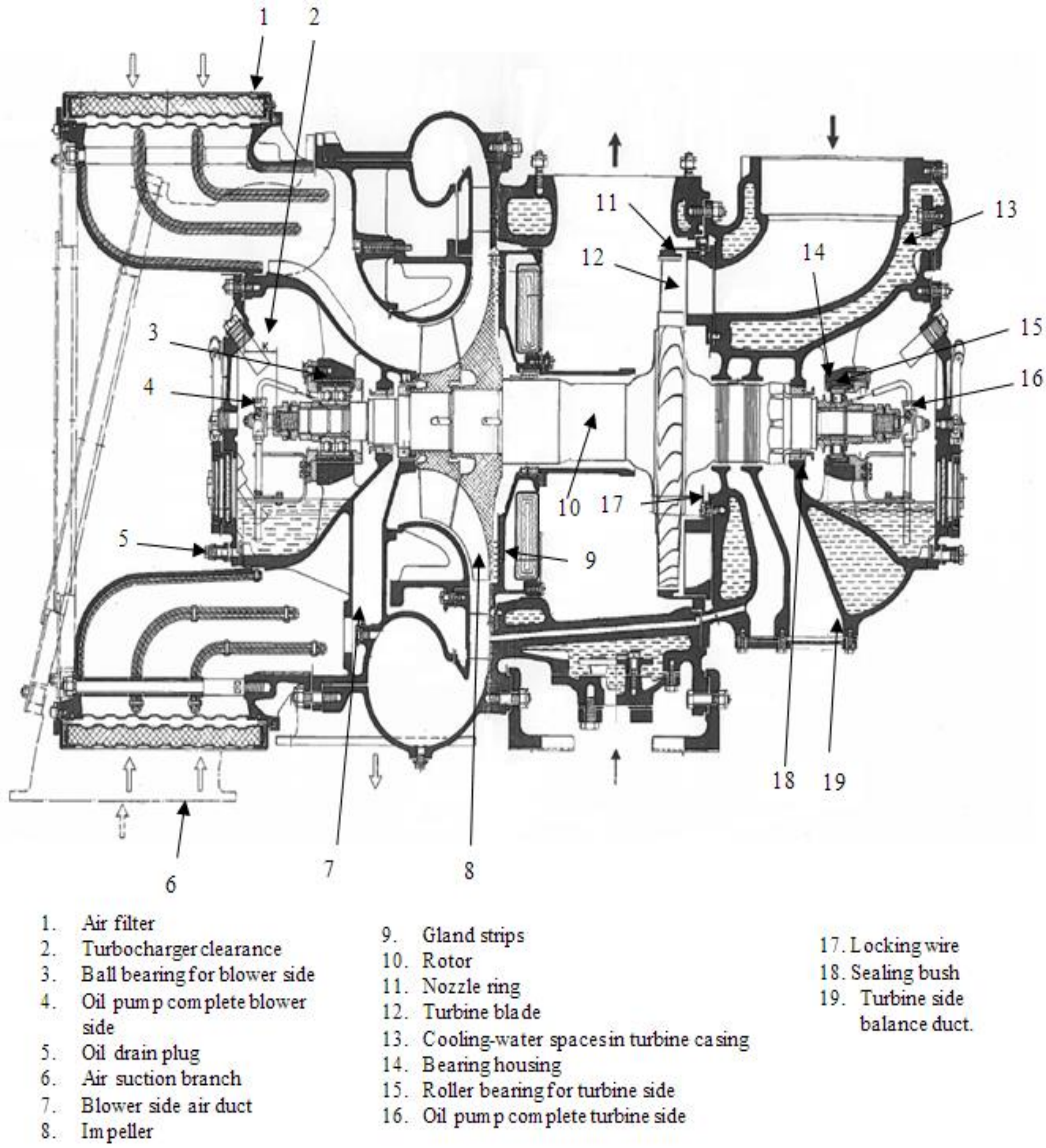


Figure 4-4: Schematic of a marine engine exhaust gas turbocharger (Bovery, 1995)

There are three steps in the developed methodology to estimate the HEPs for the maintenance procedures of a marine engine's exhaust gas turbocharger. The first step is to select the scenario and identify the sub-activities. In this study, a scenario is selected considering particular marine environmental and operational conditions for the maintenance procedure of a marine engine exhaust gas turbocharger. The selected scenario requires a second engineer to conduct three maintenance activities. The second engineer is completely familiar with these activities but has given them less importance due to over confidence, and keeps track of progress in an improper way. Moreover, the maintenance activities do not have adequate information available for accuracy checks. Furthermore, the second engineer is performing maintenance activities in moderate sea conditions, medium level of ship motion and high level of noise and vibration. In the meantime, the chief engineer has asked the second engineer to finish the activities in a shorter time than usual, as he is required to conduct more activities due to the sickness of the third engineer.

The maintenance of a marine engine exhaust gas turbocharger includes three activities and eighteen sub-activities. The sub-activities are identified according to the demand of the maintenance activities which are required to be performed in the particular scenario in marine operations.

Table 4-7: Marine engine exhaust gas turbocharger maintenance activities and sub-activities

Activity	Sub-activity	
1. Cleaning	1.1	Air filter cleaning
	1.2	Cooling–water spaces in the turbine casings cleaning
	1.3	Bearings and bearing housings cleaning
	1.4	Turbine side cleaning
	1.5	Blower side air duct cleaning
2. Dismantling and reassembling the turbocharger	2.1	Removing and replacing the bearing units
	2.2	Removing and replacing the rotor
	2.3	Dismantling and reassembling the rotor
	2.4	Removing the nozzle ring
3. Replacing individual parts	3.1	Nozzle ring replacement
	3.2	Sealing bushes replacement
	3.3	Gland strips replacement
	3.4	Turbine blades replacement

	3.5	Anti-corrosion plugs and baffles replacement
	3.6	Ball and roller bearings replacement
	3.7	Oil pumps with integral lubricating system replacement
	3.8	Checking the clearances after an overhaul

Air filter cleaning is the first sub-activity for maintenance procedures of a marine engine exhaust gas turbocharger. It requires being cleaned periodically depending on the installation and operating conditions. It has an advantage that each part of the filter can be replaced using clean/spare tools. Similarly, the cooling-water spaces of the turbine casings should be periodically checked for contamination or deposits and cleaned as necessary. In order to clean cooling–water spaces in the turbine casing a 5% hydrochloric acid solution is required. An inhibiter should be added to the chemical solution (normally 0.2% Propargyl Alcohol) to decrease the corrosion of cooling water spaces.

Bearings and bearing housings should be cleaned with kerosene which has 20% clean mineral oil. In turbine side, the sealing -air duct, the balance duct, and the guard must be cleaned. The aluminium sealing bush must be firmly placed in the casing and its grooves need to be undamaged and free from dirt. Similarly, in blower side balance duct, sealing air-duct and the nozzle must be cleaned. The blower can be cleaned by injecting water during operation. In the case of heavy and hard deposits, the blower may need to be cleaned by water injection only after dismantling. The water does not act as a solvent but the impacts of the individual droplets remove the deposit mechanically. The use of pure water without any solvent additives is recommended, by the manufacturer, to be used. The water should not contain any water additives which would cause additional deposits on the impeller. Periodic cleaning of the blower prevents contamination but does not replace periodic overhaul, by completely dismantling, of the turbocharger.

To remove and replace the bearing units in blower side, it is first required to take off the oil drain plug in order to drain the oil. It is then required to remove bearing cover, screws, washers with locating spring, and locking wire. It is also necessary to unlock the cap nut for removing the oil pump. For removing the whole bearing unit, it is then necessary to screw the extractor to the inner bearing bush. A new bearing unit is normally replaced after carefully cleaning the bearing housing. For removing and replacing the rotor, the turbocharger is firstly required to be detached from the engine. Next, it is necessary to remove the suction branches and take out the bearing unit and then remove the air-intake casing to remove the rotor. However, dismantling the rotor is only required in exceptional circumstances (i.e. to renew the gland strips of the partition wall and guide bush). Under normal circumstances, the nozzle ring does not need to be removed. This item has to be replaced when it is damaged. During manufacturing, the nozzle ring is partially sawn through for technical reasons which is quite a normal. If further cracks are observed in the ring, apart from these splits, the ring should be renewed. Worn-out sealing bushes are required to be replaced. The new bushes should be peened over at the edges until firmly in position. In order to remove the gland strip from the groove, a chisel must be used (Bovery, 1995) . Prior to gland strip removal, the chisel needs to be used carefully so that grooves will do no damage. To replacement the gland strips it should be possible to press the gland strips into the grooves without appreciable pressure. The broken/distorted turbine blades and damping wires must be renewed in accordance with the manufacturer’s specific instructions. Anti-corrosion plugs are located in the gas inlet/outlet casings as well as in the water chambers of the air cooler. Additionally, baffles are located in the cooling water inlet. The bearing unit on the blower side is simply replaced as a complete unit. The reconditioning of used bearing unit is required to be undertaken by a skilled person. In order to protect it from corrosion, this bearing unit must be well-greased. All oil pumps must be checked for wear and leakage after 16000 running hours for turbochargers with an air pressure ratio reaching up to 2:4. Checking the clearances of the turbocharger is only necessary after an overhaul.

In step-1, after selecting the scenario and identifying sub-activities for maintenance procedures, the generic task type and nominal human unreliability needs to be selected from Table 4-1for each of the sub-activities. In step-2, EPCs, EIFs and multiplier of nominal probability are selected for the defined scenario from Table 4-2 and Table 4-6. The SAPOE is then assigned between 0-1 for all the selected EPCs and EIFs. Assessed effects are calculated considering Equation 4-1. The HEP of each sub-activity is then estimated by multiplying the selected nominal human unreliability with nominal amount of SAPOE related to each EPC and EIF.

To briefly demonstrate the procedure a detailed calculation for the sub-activity 1.1, "cleaning air filter," is described. The first step is scenario selection and identifying the sub-activity for the maintenance procedures which are described in section 4.4. Then a generic task related to the sub-activity is selected. In the case of sub-activity 1.1, task H is considered from Table 4-1 which shows nominal unreliability is 0.00002. In the second step, EPCs are identified and the maximum predicted multiplier of nominal probability related to the sub-activity based on the scenario is selected. In the third step, a proportionate weight factor is applied on the maximum predicted multiplier of nominal probability which is shown in the "SAPOE" column in Table 4-8. Using Equation 4-1, assessed effect of each EPC and EIF are estimated. Finally, the assessed effect multiplied with nominal human unreliability and the HEP estimated for sub-activity 1.1 is estimated 1.16E-04.

Table 4-8: HEP estimation for sub-activity 1.1

Activity 1.0	**Cleaning**				
Sub-activity 1.1	Air filter				
Generic Task (Step-1)	Nominal Human unreliability (Step-1)	EPCs and EIFs (Step-2)	Multiplier of nominal probability (Step-2)	SAPOE (Step-3)	Assessed Effect (Step-3)
H	0.00002	Less importance given to the task	×1.4	0.10	1.04

		Improper way to keep track of progress during maintenance activity	×1.4	0.13	1.052
		Inadequate information for accuracy checks for the maintenance tasks	×2.5	0.15	1.225
		Moderate weather condition	×1.90	0.59	1.531
		Medium level of ship motion	×1.90	0.61	1.549
		High noise and Vibration level	×2.11	0.74	1.821
		Mid-range of workload and stress	×1.0	0.37	1.0
Total assessed effect					5.789
HEP					1.16E-04

A similar procedure is followed to estimate HEP for other sub-activities for the maintenance procedures of a marine engine exhaust gas turbocharger and results are represented in Figure 4-5.

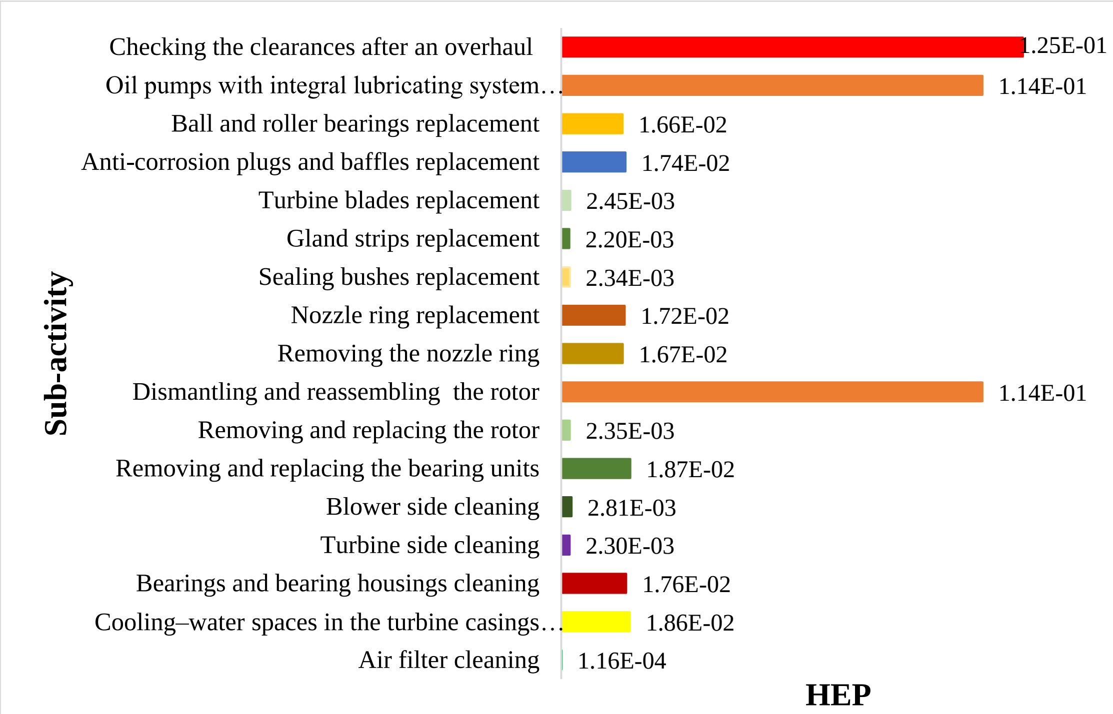


Figure 4-5: HEP for the sub-activities

The results of the case study demonstrate that estimated HEPs for the maintenance procedures of marine engine exhaust gas turbocharger sub-activities are in the range of 1.16E-04 and 1.25E-01. In this case study, high level of noise and vibration, moderate weather condition, medium level of ship motion are the highest contributing factors to making errors in the sub-activities. On the other hand, inadequate information for accuracy checks, improper ways of keep track of progress and less importance given to sub-activities, are comparatively less contributing factors to making errors.

For the selected scenario case study, some of the EPCs multiplier of nominal probability are higher than the EIFs. However, the EIFs have higher influence on unreliability so, SAPOE is higher than the EPCs as a result the EIFs creating more chances of error. For example, the EPC for inadequate information for accuracy checks for the maintenance sub-activities has multiplier of nominal probability of 2.5 and the SAPOE of 0.15. As a result, the calculated assessed effect is 1.225. On the other hand, the EIF, moderate weather condition has multiplier of nominal probability of 1.90 and the SAPOE of 0.59. As a result, calculated assessed effect is 1.531. This means that EIFs has the higher effect on making the error by seafarers during the particular maintenance sub-activities. In this case study, selected scenario for all the sub-activities is the same. However, the HEPs for all the sub-activities are not the same as the nature of each sub-activity is different. For example, the sub-activity of cleaning an air filter is easy to perform and normally seafarers respond correctly to the system which is similar to task type H of the HEART generic categories shown in Table 4-1. Therefore, this sub-activity is considered a task type H and nominal human unreliability is 0.00002. It is showing that nominal human unreliability for sub-activity of checking the clearance after an overhaul is 1000 times higher than the sub-activity of cleaning air filter. In other words, the expected HEP for the sub-activity of checking the clearance after an overhaul is also higher. Therefore, in the developed methodology, the HEP for an individual sub-activity is dependent on the nature of the sub-activity.

The developed methodology assists seafarers to recommend suitable measures for the sub-activities with the higher and lower HEP in order to reduce the probability of human error. In this case study, highest HEPs are related to sub-activity (I) checking the clearances after an overhaul, followed by (II) replacement of oil pumps with integral lubricating system and (III) dismantling and reassembling the rotor respectively. Among the 17 considered sub-activities for the maintenance procedures of a marine engine exhaust gas turbocharger, sub-activity (I) has the highest HEP. This sub-activity is related to the precision measurement and is critical for a second engineer. The complex sub-activity is required to be performed at the highest level to avoid risk, and it creates extreme stress on the second engineer and increases the HEP (Kumar and Sinha, 2008). In comparison, the sub-activity of cleaning an air filter has the lowest HEP as it is straightforward to perform and hence, does not create much stress for the second engineer. As a result, it can be performed comfortably with the low potential HEP.

4.5 Conclusions

To keep up with the demand of maintenance activities in marine operations, a great deal of human error is expected to occur which in turn may increase the risk of a shipping accident. In this study, a new human error probability assessment methodology is developed by revising the conventional HEART to estimate the HEP for the maintenance procedures in marine operations during various environmental and operational conditions. The EPC and EIF tables are developed in this study considering the most important factors that influence seafarers to make an error during maintenance activities. The developed methodology is user-friendly to apply and does not require human reliability assessment expert to perform the task. The developed methodology is applied to estimate the HEP for the maintenance procedures of a marine engine exhaust gas turbocharger as a case study. In the case study, a scenario is selected considering particular marine environmental and operational conditions for different maintenance sub-activities of marine engine exhaust gas turbocharger. Based on the selected scenario, HEP are estimated for each sub-activity presenting highest and lowest probability of human errors. Among the considered sub-activities, highest probability of error is found to be checking the clearances after an overhaul and lowest HEP is found to be for cleaning air filter. It is intended that the application of the developed methodology will help to reduce the HEPs as well as incidents and accidents during the maintenance activities in marine operations.

5. Human Error Probability Assessment during Maintenance activities of Marine Systems

Structural Abstract

Objective: The objective of this to study to develop Human Error Probability model considering various internal and external factors affecting the seafarers' performance.

Background: Maintenance operation on-board ships are highly demanding. Maintenance operation is intensive activities requiring high man machine interaction in challenging and evolving conditions. The evolving conditions are weather conditions, workplace temperature, ship motion, noise and vibration and workload and stress. For example, extreme weather condition affects the seafarers' performance hence increasing the chances of error and consequently, can cause injuries or fatalities to personnel. An effective human error probability model is required to better manage maintenance on board ships. The developed model would assist in developing and maintaining effective risk management protocols.

Method: The human error probability model is developed using probability theory applied to Bayesian Network. The model is tested using the data received through the developed questionnaire survey of more than two hundreds experienced seafarers with more than five years of experience. The model developed in this study is to find out the reliability of human performance on particular maintenance activities.

Results: The developed methodology is tested on the maintenance of marine engine's cooling water pump for engine department and anchor windlass for deck department. In the considered case studies, human error probabilities are estimated in various scenarios and the results are compared between the scenarios and the different seafarer categories. The results of the case studies for both departments are also compared.

Conclusions: The developed model is effective in assessing human error probabilities. These probabilities would get dynamically updated as and when new information is available on either internal (i.e. training, experience and fatigue) or external factors (i.e. environmental and operational conditions such as weather conditions, workplace temperature, ship motion, noise and vibration and workload and stress) changes.

Keywords: Reliability assessment, Maintenance operation, Marine system, Human factors, Human error probability.

5.1 Introduction

International Maritime Organization (IMO) accident investigation reports cite that about a quarter of all maritime accidents are initially due to machinery failure (Dobie, 2015). Therefore, maintenance of the machinery in marine systems is very important. Moreover, maintenance of the machinery also minimises the severity of the failure, prevents unexpected downtime, extends the life of the machinery and helps to decrease the number of accidents. Maintenance of on-board ship machinery is conducted by the seafarers and expected to contain unintentional errors. According to a previous accident investigation report, around 80% of shipping accidents are due to human error (Fotland, 2004). Examples of previous accidents due to human error during maintenance activities on marine machinery are explained in Islam et al. (2016a). Different internal and external factors affect the seafarers' performance and sometimes those factors are responsible for the human error. Internal factors such as lack of training and experience, and high level of fatigue have significant impact on seafarers' performance (Hystad and Eid, 2016). Performance Shaping Factors (PSFs) are the aspects of human behaviour (internal factors) or environment (external factors) that affect the human performance. PSFs have either positive or negative impact on seafarers' performance. For example, high level of training and experience has a positive impact on seafarer's performance whereas, high level of fatigue has a negative influence on seafarers' performance. Details about the lack of seafarers training, experience and high level of fatigue are explained in Islam et al. (2016a). Moreover, external factors affecting the seafarers' performance include marine environmental and operational factors and these also have a significant impact on seafarers' performance. Marine environmental factors such as weather conditions, workplace temperature and operational factors such as ship's motion, workload and stress and noise and vibration have significant influence on seafarers' performance (Islam et al., 2017a).

According to an investigation by the United Kingdom Protection and Indemnity (UK P&I) Club, accidents related to human error cost the shipping industry around

$541 million per year (Dhillon, 2007). Furthermore, human error related accidents also result in major injury and loss of life to seafarers. Therefore, human error assessment is one of the vital components in probabilistic risk analysis for the shipping industry to reduce risk of accidents.

Researchers (Abbassi et al. (2015); Deacon et al. (2013); Dhillon (1987); DiMattia (2004); Islam et al. (2016); Noroozi et al. (2013)) applied the human reliability assessment techniques to several engineering applications. Deacon et al. (2013) applied this concept to investigating human performance in offshore platform musters. Khan et al. (2006) applied this technique to analysing the human performance in offshore evacuations systems. Noroozi et al. (2013) investigated this technique in pre- and post-maintenance procedures of offshore oil and gas facilities. Recently, Hoboubi et al. (2017) studied the impact of job Stress and satisfaction on workforce productivity in an Iranian petrochemical industry. In another efforts, Islam et al. (2016a) estimated the human errors during maintenance procedures of marine engines. The previous studies mentioned above proved the importance of estimating human errors in risk assessment of various engineering systems. Furthermore, IMO (2002) guidelines proposed adopting the human error probability assessment to enhance the safety of shipping industry.

Some of the most common available human error likelihood techniques are; Technique for Human Error Rate Prediction (THERP) by Swain and Guttmann (1983), Success Likelihood Index Method (SLIM) by Kirwan (1994) and Human Error Assessment and Reduction Technique (HEART) by Williams (Williams, 1986). THERP approach does not offer suitable guidance to represent the Error Producing Conditions (EPC) and scenario development (Jae and Park, 1995), however, it does not offer suitable guidance to represent the Error Producing Conditions (EPC) and scenario development (Jae and Park, 1995). SLIM approach is based on expert judgement and various uncertainties affected the final outcomes (Musharraf et al., 2013). HEART have some doubts over the consistency of the method as dependency and interaction among contributory factors to EPC is not accounted for in this approach (Noroozi et al., 2014c). Additionally, most of the above-cited approaches assume unrealistic independence among human factors, and associated actions. None of the aforementioned techniques have the capability of updating probability when new information is available. Updating probability is important to reanalyse posterior HEP instantly based on newly available information.

Bayesian Network (BN) is a mathematical graphic based model represented by each variable as a node with the directed links forming arcs between them. BN provides a natural way to handle missing data, allows a combination of data with domain knowledge, and assists in learning about causal relationships among variables (Heckerman et al., 1995). Moreover, BN provide fast responses to queries (Musharraf et al., 2013). BN has been applied in various industries for assessing the HEP (Groth and Mosleh, 2011; Heckerman et al., 1995; Mu et al., 2015; Musharraf et al., 2013). Groth and Mosleh (2011) applied BN for predicting HEP in nuclear power industry. Mu et al. (2015) applied BN in predicting the HEP in the aviation industry. Musharraf et al. (2013) applied BN to human reliability assessment during evacuation in offshore emergency conditions.

The main objective of this paper is to develop a human reliability assessment technique for more accurate HEP assessment in the maintenance activities of marine operations using BN. Application of the developed methodology will help the shipping industry to assess the probability of seafarers' error accurately. Additionally, the developed methodology will assist in improving the safety and reliability of the maintenance activities of marine operations. The methodology developed in this study is based on BN and has the capability of dynamic updating when new information about the state of internal and external factors available.

BN will also help represent the relationships between human factors and seafarers' actions in a hierarchical structure. In this paper, section 2 provides fundamental description of BN; section 3 explains the development of methodology; section 4 details development of BN model; and section 5 demonstrates the application of the developed technique to case studies. Results and discussions are presented in section 6. Finally, section 7 summarises and concludes the paper.

5.2 Fundamentals of BN

BN is a probabilistic model which represents interaction of variables through the direct acyclic graph and Conditional Probability Tables (CPTs) (Pearl, 2014). The networks consist of nodes and edges. Each node represents a probability of distribution either discrete or continuous. The nodes represent a set of random variables and edges joining the nodes represent direct dependencies between the variables. Generally, BN comprises quantitative and qualitative sections. The conditional probabilities associated with the variables are the quantitative section and nodes and edges are the qualitative section of the network. The relationship between the nodes is described using CPTs. All the variables of the network are presented in a CPT. The CPT provides a broad description of probabilistic interaction. A CPT also has the ability to model the probabilistic dependency among a discrete node and its parent nodes. The probabilities in the CPT denote the probabilities of each state given the state of the parent variable. Conversely, if a variable in BN does not have parent variables, the CPT denotes the prior probability variable (Kraaijeveld et al., 2005). If there are "n" variables $X_1, X_2, \dots \dots, X_n$, in the network and $Pa(X_i)$ represents the set of parents of each X_i, then joint probability distribution for the network estimated as:

$$P(X_1, X_2, \dots \dots, X_n = \prod_{i=1}^{n} P(X_i|PaX_i)) \quad (1)$$

Where, $P(X_i|Pa(X_i))$ is the discrete conditional probability distributions of X_i given its parents. Thus the following information is required to develop BN model.

- $X_1, X_2, \dots \dots, X_n$, set of variables (nodes)
- The interaction (edges) among the variables
- $P(X_i|Pa(X_i))$ conditional probability distribution for each variableX_i.

Section 4 illustrates the BN model for the maintenance activities of marine operations.

5.3 Methodology

The methodology developed, based on the BN approach, is used in this study to estimate HEP for the maintenance procedures of marine operations. The use of BN will help to represent a relationship between human factors and actions to estimate the HEP.

There are three main steps in developed methodology to estimate the HEP as illustrated in Figure 5-1.

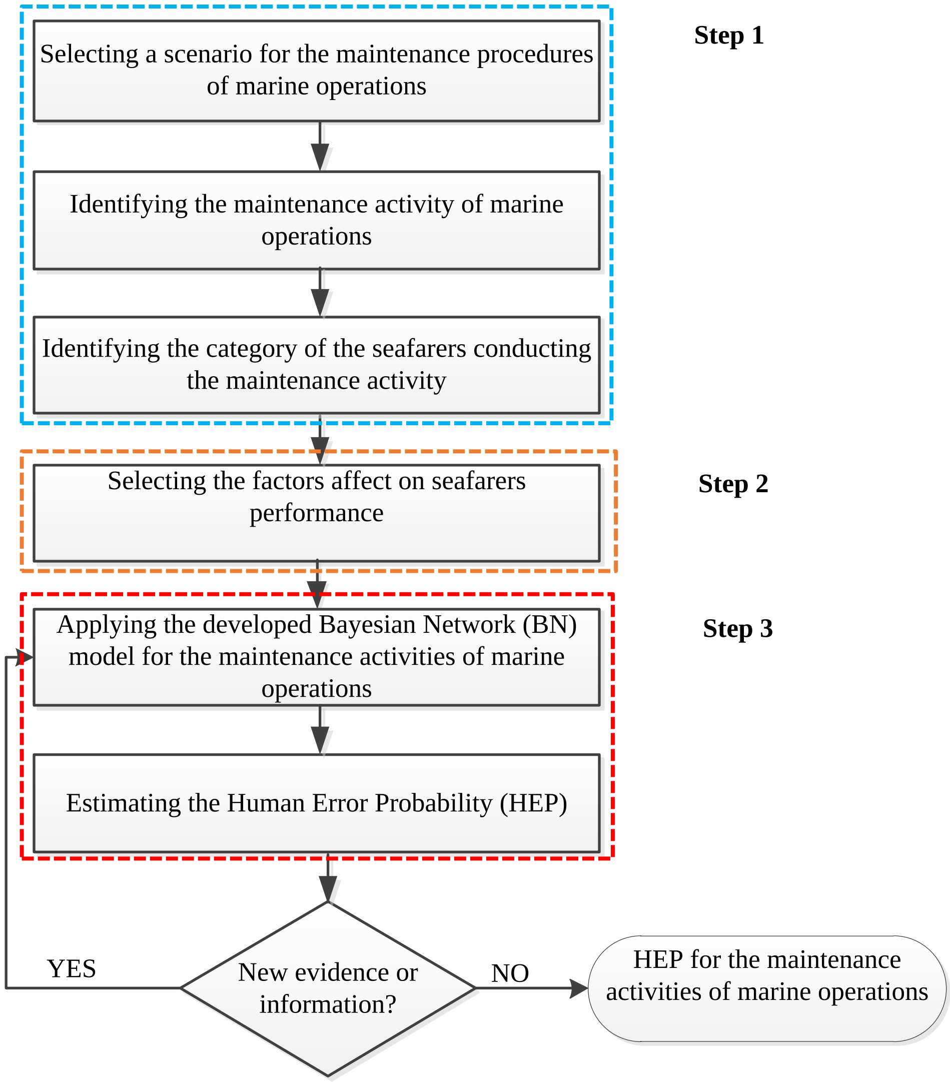


Figure 5-1: Developed methodology for estimating the HEP during the maintenance activities of marine operations

In step 1, scenario selection, identification of the maintenance activity and category of the seafarers for the maintenance procedures of marine operations are required. To select a scenario an impact of marine environmental and operational conditions affecting on-board operations is necessary. Similarly, it is essential to identify the type of maintenance activity requiring to be performed based on the maintenance schedule/ emergency situation. It is then necessary to identify the category of the seafarers conducting the maintenance activity. The seafarers in this study are categorised in four categories; A, B, C and D. These seafarer categories depend on the level of the seafarers' training, experience and fatigue. Dividing the seafarers into different categories based on their rank, experience and duration of the voyage are discussed in detail in section 5.4.2.1.

In step 2, it is necessary to select the factors that affect the seafarers' error making during on-board maintenance activities. Both, internal and external performance-affecting factors are selected in this study as PSFs are considered in two different categories (Musharraf et al., 2013). Furthermore, most important performance factors are selected according to the expert's opinion. The internal factors are training, experience and fatigue, while the external factors are environmental and operational conditions. The environmental factors are further categorised as weather conditions, workplace temperature and operational factors are ship motion (roll and pitch), workload and stress, and noise and vibration. These factors are selected according to the previous studies by (Colwell, 2005; Driskell and Salas, 2013; Hancock, 1981; Matsangas et al., 2014). It should be noted that seafarers' opinions are also taken into account prior to selecting these factors. Each seafarer has more than five years' experience in the maintenance activities on board ship. The selected performance affecting factors in this study possibly have an influence on each other. However, only the individual effect of the factors on seafarers' performance is considered in this study. The states of each selected external factor are also selected considering expert's opinion as mentioned above.

The final step (step 3) is to apply the developed BN model and estimate the HEP. If there is no new information available regarding seafarers' performance affecting factor, then it will be final the HEP for that maintenance activities of marine operations. However, if new information is available, then it is essential to go back to the start of step 3 in order to add the new evidence to update the estimated HEP.

5.4 Development of a BN model for the maintenance activities of marine operation

As outlined in section 5.3, the methodology developed in this study is based on the BN approach. The unique feature of the BN will allow accurate estimation of the

HEP. To develop the BN model, firstly all the root causes that are not directly influenced by any other variables are selected. The variables are selected according to the experienced seafarers' opinions. These variables affect the seafarers' performance during the maintenance activities on-board. All the root causes are each then assigned a node, as illustrated in Figure 5-2. In the second step, all the variables such as external and internal factors directly influenced by the root nodes are also selected according to the experienced seafarers' opinions. This hierarchical process continues until the network is completed. The final network for the maintenance activities in marine operations is illustrated in Figure 5-2.

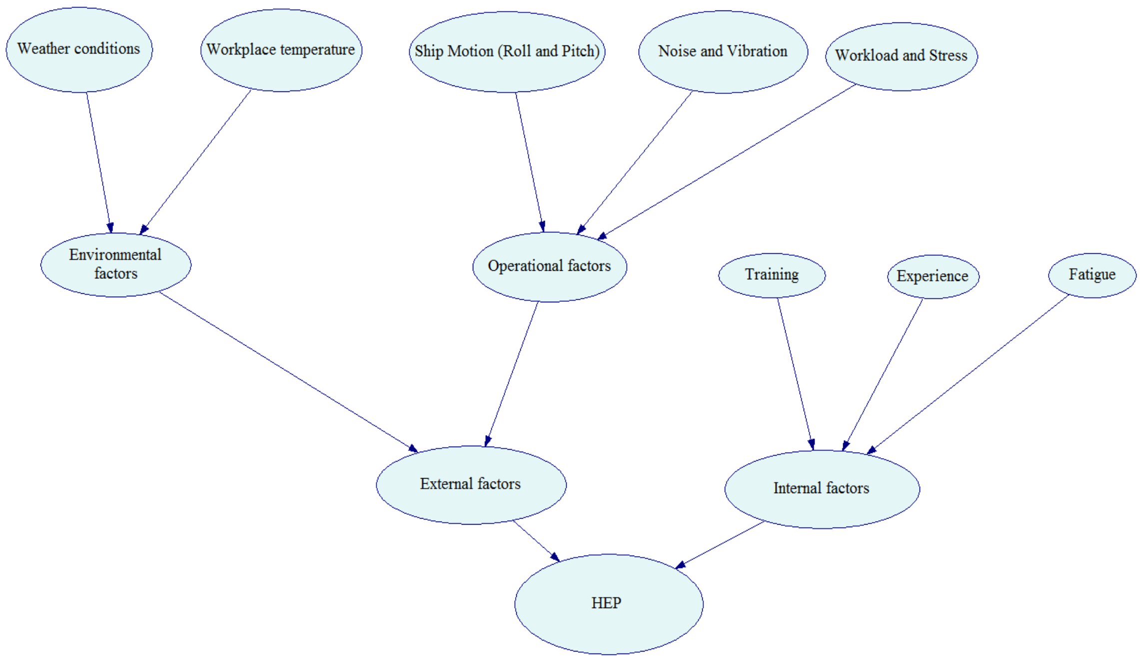


Figure 5-2: BN model for the maintenance activities of marine operation

BN model requires prior probability for the parent nodes and CPT for the child nodes. Details about the prior probabilities and CPT's are discussed in the following sections.

5.4.1 Prior Probabilities

In this study, prior probabilities are considered as a first approximation of the conditions. The prior probabilities are provided by experienced seafarers who have more than 10 years' experience as a marine engineer. The prior probability values range between 0 to 1 ("0" lowest and "1" highest). Prior probabilities for the internal and external factors are illustrated in Table 8-1and Table 8-2 respectively. On-board ship, there are two departments, Engine Department (ED) and Deck Department (DD) who are responsible for maintenance activities. The nature of the maintenance activities and working environment in ED differs from that of the DD and affects seafarers' performance differently. ED seafarers perform the maintenance activities in the engine room and DD seafarers normally perform their maintenance activities on the weather deck. Prior probabilities for all categories of seafarers (A to D) of ED and DD are similar for internal and external factors.

In Table 8-1, internal factors' prior probability illustrates that whenever the levels of training and experience are high and the level of fatigue is low, the prior probability is low and vice versa. Moreover, in Table 8-2, external factors' prior probability shows that, in marine environmental and operational conditions, weather, workplace temperature, ship motion (roll and pitch), noise and vibration and workload and stress have a "normal" state rather than a "moderate" state. It is also less likely to have "high/extreme" state.

5.4.2 Development of CPT for the BN model

There is a lack of available CPT data for the maintenance activities in marine operations. As a result, it is necessary to develop CPT for BN model. BN model requires CPTs for environmental, operational, internal, external factors and HEP for the maintenance activities of marine operations. CPT for the environmental and operational factors are developed by conducting a questionnaire survey among experienced seafarers around the world. On the other hand, CPT for internal, external factors and HEP for the maintenance activities of marine operations are developed based on expert judgment.

As mentioned earlier although ED and DD seafarers perform their tasks separately, some of the environmental and operational factors in ED may affect the seafarers' performance differently than those in DD. Therefore, it is necessary to develop the environmental and operational factors CPT separately for both departments.

There are three steps to develop the CPT for environmental and operational factors as illustrated in Figure 5-3. In step-1, a questionnaire was developed to determine the impact of the selected child nodes (variables) in order to develop the CPT.

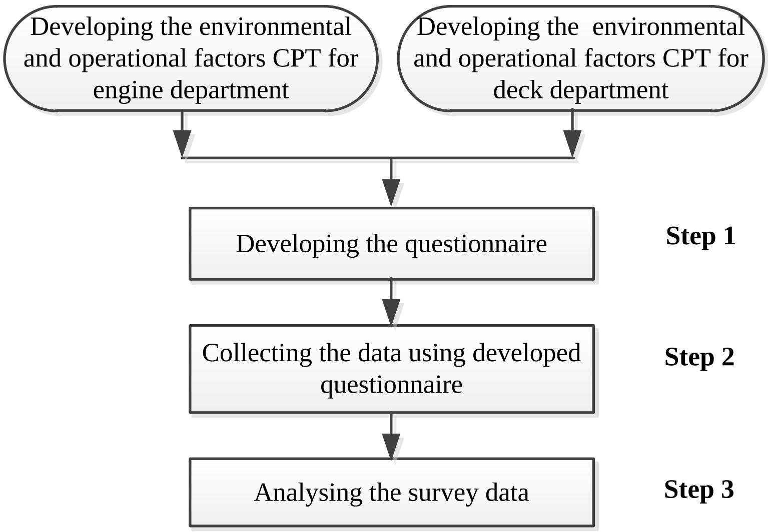


Figure 5-3: Development of a CPT for the environmental and operational factors

The developed questionnaire was reviewed by the experienced seafarers prior to conducting the survey. In step-2, a Survey Monkey link was created to conduct the data collection. Details about the development of the questionnaire and data collection are explained in Islam et al. (2017a). The Survey Monkey link was sent to a total of 400 experienced seafarers around the world, 200 in each department (i.e. engine and deck). In step-3, Seafarers' survey data was received from ED and DD and the CPT for both of the departments was developed.

5.4.2.1 Environmental and operational factors CPT for ED

A total of 121 responses were received from the engine department (response rate of 60.5%). The received survey data was then categorised according to the seafarers' level of training, experience and fatigue. Prior to categorising the data, it was considered that failure or success of a maintenance activity depends on skill levels. Seafarers of ED hold various ranks on ships. All these ranks require a certain level of training and experience. These ranks for ED are chief engineer, second engineer, third engineer, fourth engineer and cadet engineer from highest to lowest respectively. Category "A" is considered the (highest rank) chief engineer with 10 years or more experience and voyage duration of 1 month. Category “B” is allocated to second engineer with 8 years’ experience and voyage duration of 2 months. Category “C” relates to third engineer with 6 years’ experience and voyage duration of 3 months. Category “D” is the fourth engineer with 5 years’ experience and voyage duration of 4 months. Though the cadet engineer is also part of the ED, he/ she has not been considered in this study as a cadet engineer is always supervised by the upper ranked seafarers’.

Among the 121 survey responses, category A, B, C and D level responses are 31, 45, 25 and 20 respectively. The CPTs are developed for all the categories individually. The CPTs for environmental factors are developed by using the Equation 5-3.

$$\mathbf{Dependency} = \mathbf{1} - \frac{\mathbf{V}}{\mathbf{5}} \qquad \textbf{[5-3]}$$

Where, V is the difference between two factors considered 95% of confidence and 5 is the maximum value from the survey (as the questionnaire was developed using a five likert scale of 1 to 5, where 1 is considered to be not important and 5 extremely important respectively). If the performance affecting factors survey value is more than 1, then the dependency results are considered as a poor condition in CPT. On the other hand, if the two performance affecting factors survey value is 1 and dependency result is 1 then the result 1 considered as a good condition in CPT. The developed CPT for the environmental and operational factors for the seafarers’ categories (A to D) of the ED are presented in Table 8-3 to Table 8-10. Table 8-3 to Table 8-6 shows the CPT for environmental factors. The environmental factor “poor” is the condition where marine operations should be stopped or recommended to proceed with extreme caution (high-risk condition). Moreover, environmental factor “good” is the condition where marine operations will be continued with acceptable risk, depending upon the type of organization. CPT’s for operational factors are presented in Table 8-7 to Table 8-10 and operational factors “poor” and “good” mean the same as environmental factors “poor” and “good”.

5.4.2.2 Environmental and operational factors CPT for (DD)

A total of 114 responses were received from the engine department (response rate of 57%). The ranks for DD are captain, chief officer, second officer, third officer and deck cadet. All these ranks require a certain level of training and experience. Categories for the DD seafarers are considered in the same way as the ED seafarers' category. Though deck cadet is also part of the DD it has not been considered in this study. The 114 category A, B, C and D level responses received are 25, 38, 34 and 17 respectively. The CPTs are developed for all the categories individually. DD environmental factors CPTs for the seafarer categories (A to D) are the same as the ED as mentioned in Table 8-3 to Table 8-6. However, CPTs for operational factors is developed similar to ED as mentioned in section 5.4.2.1 and illustrated in Table 8-11 to

Table **8-14**.

5.4.2.3 CPTs for the internal and external factors, and HEP for the maintenance activities of marine operations

The CPT's for internal factors, external factors and maintenance activities of marine operations are the same for all the seafarers' categories (A to D) and were developed according to the expert's opinions. Table 8-15 illustrates the CPT for the seafarers' internal factors. The CPT values range from 0 to 1 where "0" is lowest and "1" the highest. If any of these two factors (i.e. training and experience level are high or the fatigue level is low, the probability of internal factor is good and vice versa. However, CPT for seafarers' external factors values are 0 and 1 as illustrated in the Table 8-16. When any of the factors (environmental /operational) are considered as poor, the probability of external factor is "poor". On the other hand, when both of the factors (environmental and operational) are good, then the probability of external factor is "good".

The CPT for maintenance activities of marine operations is illustrated in Table 8-17. When both factors (internal and external) are bad, then the probability of maintenance activities is "failure". However, when internal factor is bad and external factor is good, then it is uncertain whether the maintenance activity is "failure" or "success". Moreover, when internal factor is good and external factor is bad, then the probability of maintenance activity is "failure" (considering the external factors influence seafarers' performance more than the internal factors). The CPTs for internal factors, external factors and HEP estimation of maintenance activities of DD is developed similar to ED and illustrated in Table 8-15, Table 8-16 and Table 8-17 respectively. By computing the developed CPTs and using prior probability received from the experts, BN model is developed for the maintenance activities of the marine operations.

5.5 Application of the Methodology: Case Study

The developed methodology is applied in two different case studies. In the first case study, the developed methodology is applied for the maintenance procedures of a marine engine's cooling water pump to estimate the HEP (for ED). Maintenance of the cooling water pump is very important as it helps in cooling the marine engine to reduce the damage to its material. In the second case study, the developed methodology is applied for the maintenance procedures of an anchor windlass to estimate the HEP (for DD). An anchor windlass is a device used for ship anchor handling. To get the desired output from the windlass, maintenance is essential.

5.5.1 Case Study 1 (Engine Department)

There are three steps in the developed methodology to estimate the HEPs for the maintenance procedures of a marine engine cooling water pump. The first step is the scenario selection, identification of the maintenance activity and categorisations. In this case study, two scenarios are selected according to the marine environmental and operational conditions.

In the first scenario, a ship is at berth and seafarers (category A/ B/ C/ D) are conducting the maintenance of marine engine cooling water pump. The seafarers are performing the maintenance activity in normal weather conditions, normal workplace temperature in the engine room, low level of ship motion, mid-range of workload and stress level and low level of noise and vibration.

In the second scenario, the same seafarers (category A/ B/ C/ D) are conducting a similar maintenance activity. However, considering the existing conditions, new information is available that weather condition, level of ship motion, level of workload and stress are the same but the workplace temperature changes from normal to extreme, and noise and vibration level increases from low to high. In the second step, the factor affecting the seafarer's performance is selected according to the specified scenario. Finally, the BN model developed for the maintenance activities of marine operations is applied in order to estimate the HEP for the maintenance procedures of a marine engine cooling water pump. However, for the second scenario, the seafarers' performance affecting factors are updated according to the new available information and the BN model is applied to estimate the new HEP.

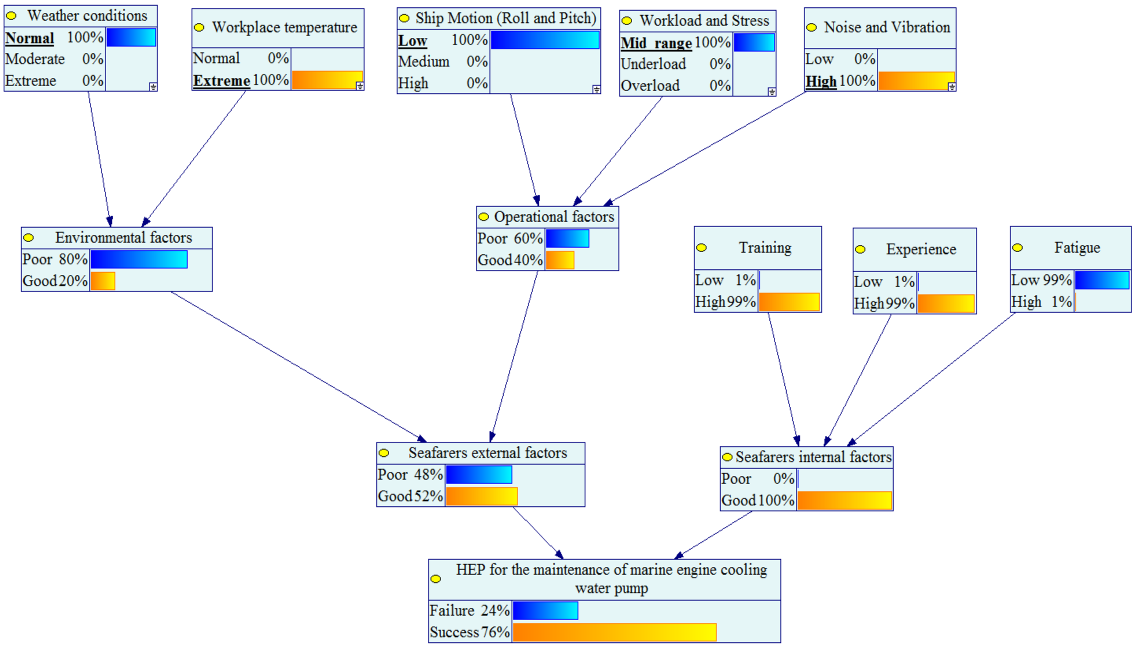


Figure 5-4: Developed BN to estimate the HEP for the maintenance of marine engine cooling water pump (scenario 2, category-A)

Similarly, considering all the other categories (A, B, C and D) of scenario 2, HEP results are obtained and presented in section 5.6.

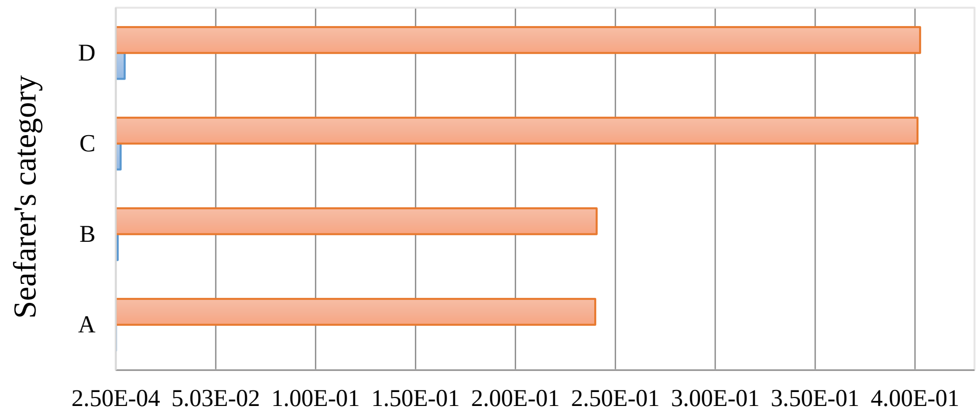
5.5.2 Case Study 2 (Deck Department)

The developed methodology is also applied to estimate the HEPs for the maintenance procedures of an anchor windlass. In this case study, two different scenarios are selected according to the marine environmental and operational conditions. In the first scenario, a ship is at berth and seafarers (category A/ B/ C/ D) are conducting the maintenance of an anchor windlass. The seafarers are performing the maintenance activity in normal weather conditions, normal workplace temperature on the weather deck, low level of ship motion, workload and stress level is mid-range and low level of noise and vibration are experienced.

In the second scenario, the same group of seafarers (categories A/ B/ C/ D) are conducting the similar maintenance activity. However, considering the existing conditions, new information is available that weather condition, level of ship motion, level of workload and stress are same but the workplace temperature changes from normal to extreme, and noise and vibration level increases from low to high. In the second step, the factors affecting the seafarer's performance are selected according to the scenario. Finally, the developed BN model for the maintenance activities of marine operations are applied in order to estimate the HEP for the maintenance procedures of an anchor windlass. However, for the second scenario, the seafarers' performance affecting factors are updated according to the new available information and the BN model to estimate HEP. Seafarers DD case studies of scenarios 1 and 2 are also obtained in the similar way as ED, and HEP results are presented in section 5.6.

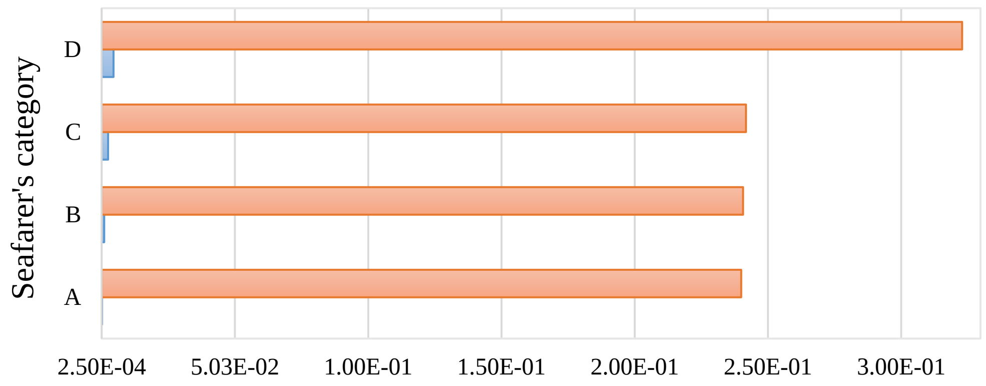
5.6 Results and discussions

The application of the developed methodology to the case studies is summarised in Figure 5-5 and Figure 5-6. In Figure 5-5 and Figure 5-6, "X" axis illustrates the categories of the seafarers and "Y" axis shows the HEPs. The HEPs for all the four categories (A to D) of the seafarers in ED and DD are estimated. Scenarios 1 and 2 of the ED illustrate the HEPs for the maintenance activity of a marine engine cooling water pump and are presented in Figure 5-5. Similarly, scenarios 1 and 2 of the DD demonstrates the HEPs for maintenance activity of the anchor windlass and results are presented in Figure 5-6.



	A	B	C	D
Scenario-2	2.40E-01	2.41E-01	4.02E-01	4.03E-01
Scenario-1	2.98E-04	1.18E-03	2.65E-03	4.67E-03

Figure 5-5: HEP estimation of the case studies for ED



	A	B	C	D
Scenario-2	2.40E-01	2.41E-01	2.42E-01	3.23E-01
Scenario-1	2.98E-04	1.18E-03	2.65E-03	4.67E-03

Human Error Probability (HEP)

Figure 5-6: HEP estimation of the case studies for DD

The case study results show that HEPs related to the seafarers from A to D category increased respectively for both ED and DD. The reason is the level of seafarers training and experience decreased and fatigue level increased from category A to D respectively. Moreover in scenario 1, HEPs for the seafarers' category A to D in both of the departments (ED and DD) depict a similar trend. This means that the level of training, experience and fatigue affects seafarers' performance. This is common in both departments. The environmental and operational conditions do not affect seafarers' performance in the considered scenario (scenario 1) because the level of these conditions are considered to be normal, mid-range and low.

In scenario 2, HEPs are increased for both department's maintenance activities due to changing the workplace temperature from normal to extreme and levels of noise and vibration from low to high. It is proved that as soon as the workplace temperature changes from normal to extreme and levels of noise and vibration from low to high, the HEPs also started to increase. Interestingly in scenario 2, seafarers' category A and B's HEP are same in both ED and DD. This confirms that extreme workplace temperature and high levels of noise and vibration affect the seafarers in both departments similarly. However, the other categories (C and D) HEPs increased in both departments. It clearly shows that the chances of error increase with an increase in the level of fatigue and a decrease in the level of training and experience. Moreover, the HEPs for seafarers' categories C and D in ED and DD have a significance difference and is higher in ED compared to DD. This means that the extreme workplace temperature and high levels of noise and vibration affect the seafarers' performance more in ED than the seafarers in DD.

The HEPs are found to be high in scenario 2 for the seafarers' categories (A to D in both the departments as mentioned above. Extreme workplace temperature decreases the seafarers' ability to concentrate on the maintenance activities and lowers the performance, thus HEPs increase. Moreover, extreme workplace temperature influences seafarers body temperature causing it to rise, which could lead to health issues, therefore, likelihood of errors increase (Hancock et al., 2007). Furthermore, extreme workplace temperature leads to loss of seafarers' body fluid which in turn decreases the performance and increases the HEP (Noroozi et al., 2014a). In the same way, high levels of noise and vibration degrade seafarers' stamina and alertness which in turn affects their performance, thus increasing HEPs. Moreover, persistent exposure to high levels of noise and vibration causes fatigue and confusion. This significantly affects seafarers maintenance activities on board ship and increases HEPs (Ross, 2009).

Furthermore, high level of noise and vibration impact on the quality of seafarers' perception, memory and reasoning thus increasing HEPs (Lundh et al., 2011).

There are some differences in the results between the seafarers' categories, as all the seafarers' categories are not affected by the same level of extreme workplace temperature and high levels of noise and vibration. Thus, the HEPs for the seafarers' category with comparatively low training and experience and high fatigue level are higher (i.e. categories C and D) than categories A and B. Due to the high level of experience, A and B category seafarers' are not affected similarly to the ones in C and D categories. Further discussion on the effect of experience on the human performance is provided by Irgens-Hansen et al. (2015).

Moreover, the HEPs for categories C and D in ED and DD have a significance difference. HEPs for categories C and D in ED are higher than in DD. This confirms that the extreme workplace temperature and high levels of noise and vibration affects the seafarers' performance more in ED than those in DD, because in ED, maintenance activities are performed in the engine room which is generally located below the waterline of the ship. Moreover, engine room machinery radiates extreme heat and the engine room does not have much air circulation and is an enclosed space. Seafarers thus feel uncomfortable and HEPs are going to increase. Furthermore, due to the enclosed space in the engine room, noise is reflected and becomes increased in intensity which affects seafarers' performance more and increases the HEP (Lundh et al., 2011). On the other hand, the maintenance activities on the DD are generally performed on the weather deck. Thus even in extreme temperature, natural air circulation is available which affects the seafarers' performance less than ED and decreases the HEPs. Additionally, on the weather deck, noise does not increase in intensity as it is not in an enclosed space, therefore, DD seafarers' are less affected by the noise compared to those in ED and HEPs are going to decrease.

One of the best advantages of the developed methodology in this study, is that once new evidence is available the likelihood of failure or success of any maintenance activities can be revised as discussed in section 5.3. Therefore, the HEPs and the probability of failures can be updated considering the existing operational and environmental conditions. The conventional human reliability assessment techniques do not have this advantage. Therefore, the developed methodology is capable of estimating the HEP more precisely.

5.7 Conclusions

The negative influence of internal and external factors affect seafarers' performance and play an important role in making errors during maintenance activities on-board. To estimate the HEP accurately, it is necessary to consider interdependency between the performance-affecting factors and seafarers' actions. The developed methodology in this study is capable of representing complex dependencies among the performance affecting factors and seafarers' actions to include uncertainty in modelling. Moreover, the developed methodology is illustrated as conditional dependencies better by means of direct causal arcs among dependent variables. The CPTs for environmental and operational factors are used in the developed methodology by conducting a questionnaire survey among the experienced seafarers' to estimate the HEP more accurately. The developed methodology is effective for both, the HEP estimation and updating in the light of new information. Therefore, the developed methodology is a superior technique to traditional HEP assessment techniques. The developed methodology is applied to estimate HEP in various real life scenarios as the case studies. The case study results show that category "A" chief engineer/captain (highest rank) with 10 years or more experience and duration of the voyage of 1 month has the lowest HEP and category "D" fourth engineer/third officer with 5 years' experience and duration of the voyage for 4 months has the highest. The HEPs fluctuate with the changes in internal or external factors. According to the HEP result, captain/ or chief engineer can select the particular category of seafarer who is most reliable to perform the maintenance activities in a particular scenario in order to reduce the HEP. Moreover, the estimated HEPs for the maintenance activities of marine operations will help to take remedial actions to reduce HEPs and shipping accidents.

6. Human Error Assessment during Maintenance Operations of Marine Systems - What is Important?

Abstract

Human errors, particularly during maintenance operations, are one of the most important causes of marine accidents. Seafarers conduct marine system maintenance on-board in a challenging environment, which makes maintenance prone to un-intentional errors. To address this concern, study of human performance during maintenance operations on ships is necessary as a part of maritime quantitative risk assessment. There is significant lack of field data and information relating to human performance on-board ships. This paper attempts to fill this important data and knowledge gap. The paper presents a data collection and analysis procedures for maintenance operations of marine systems. Data related to performance-affecting factors is collected from 400 experienced seafarers through a structured questionnaire. The collected data is then analysed for normality and also for pairwise significance test. It helps to study the generalization of the data and also to identify the relative importance of the factors. Workload and stress, and ship motion (roll and pitch) are identified as critical factors affecting seafarers' performance on on-board maintenance operation.

Keywords: Human Error, Maintenance operation, Marine system, Surveying, Data collection

6.1 Introduction

Maintenance operations of marine systems is essential to avoid unexpected down time, minimize the number of mishaps, and furthermore to increases the life of the machinery. Over the past two decades numerous accidents have occurred during the maintenance operations of marine systems due to human induced errors (Kuehmayer, 2008a; MARS, 2010; MD, 2011; TSB, 2013). Some of these accidents are discussed in Islam et al. (2016b) which details human error causation and its impact. There are many environmental and operational factors affecting seafarers' performance during the maintenance operations on-board ship (Islam et al., 2017a; Islam et al., 2017b). In these studies, the lack of appropriate data on human performance is identified as a key knowledge gap. This knowledge gap limits usability of any engineering approach to better understand and improve human performance.

The human error assessment techniques in quantitative risk assessments require numerical data (Abbassi et al., 2015; Islam et al., 2016b; Islam et al., 2017d; Noroozi et al., 2013). Currently, there is a lack of sufficient human error data to allow the maintenance operation of the marine systems to be applied by the industry and for researchers to develop an accurate technique for human reliability assessment. Therefore, collecting the relevant quantitative data on human errors which have occurred in maritime operations is unavoidable. The currently available data in the public domain (Blanco and Lewko (2002); Montewka et al. (2014); Ritmiller (1998) , specifically on the key factors affecting the human performance during maintenance operation in shipping, are qualitative and subjective in nature.

Islam et al. (2017a) studied the influential factors on seafarers' performance considering the experienced seafarers' feedback and they then analysed the available literatures. For the data collection, the experienced seafarers' feedback could have conflicting interests. Therefore, it is essential to measure the responses and the difference in the feedback on a consistent scale. It is also to be noted that to develop a broader human error assessment technique, the appropriate supposition principles need to be used.

To meet the scientific rigor and enable generalization of the data and its interpretation, various sources of data and modes of feedback, such as interviews with experienced seafarers' on-board, review of existing documentation, and a direct questionnaire method, can be used. Direct interview method offers a wide range of data (often some of the data/information unwanted) (Patton, 2005; Stanton et al., 2013; Styśko-Kunkowska, 2014). However, it is time-consuming. Furthermore, undesirable additional information may distract the focus of the study, and may be time costly. Direct interview is generally conducted face to face. Therefore, as noted (Witkin and Altschuld, 1995) in many circumstances, respondents may be hesitant to put a number into a question, and the researchers may not come up with a result. Due to the respondent's hesitation to apply a number, the interview objective is affected which will be costly time wise and a burden to find another suitable respondent. Thus, a direct interview has not been considered as a favourable option in the present study. Review of publicly available documentation is another option. However, reliable and comprehensive human error assessment data for maintenance operations of marine systems is not publicly nor widely available. Therefore, this approach is not most appropriate for the present study. The structured questionnaire method to acquire responses may be the most appropriate technique. It enables data collection from globally operating respondents. It widens the applicability of the method and helps to generalize the data and its interpretation. It is also an easy, effective, economical, flexible, and fast technique for data collection and development of a conceptual framework (Szolnoki and Hoffmann, 2013). This approach is adopted in the present study.

This study aims to use the structure questionnaire to collect the relevant data. The collected data is adopted to identify the factors important for human performance on on-board marine operations, analysing the relative importance of these factors, and the integration of these factors for human error estimation during the maintenance operation of marine systems. Collected data is analysed through a series of statistical techniques to check the diversity and generalization of the data and its interpretation.

This paper comprises five sections. Section 6.2 briefly presents the structure of the responses collection questionnaire, and section 6.3 presents the data analysis methodologies. Section 6.4 presents the main finding of the study while section 6.5 presents the conclusions. There are three appendices which present questionnaire and results of the data analysis.

6.2 Questionnaire Structure

Details of the questionnaire developed to seek feedback from the experienced seafarers are illustrated in Appendix 8.5. This section discusses the general structure of the questionnaire to better understand the responses and their interdependency.

Two departments of a ship, Engine and Deck, are responsible for the maintenance operations on-board. The type of maintenance activities and working environment in each department (Engine Department- ED and Deck Department- DD) is significantly different (Islam et al., 2017a). Therefore to be specific, the developed questionnaire was shared with the individuals in each department separately. The questionnaire structure is depicted in Figure **6-1**. In total five main seafarers' performance affecting factors are considered in this study. These are weather conditions, workplace temperature, ship motion (roll and pitch), noise and vibration, and workload and stress. All five main factors are subdivided into sub-categories as described in Figure **6-1**, details of which are briefly provided in Appendix 8.5. A detailed explanation of the developed questionnaire is available in Islam et al. (2017a). It recognises that the main factors affect human error to a certain degree in each sub-category. Questions 1-6 (Appendix

8.5) in the questionnaire seek the relative importance of the respective main factors and sub-categories.

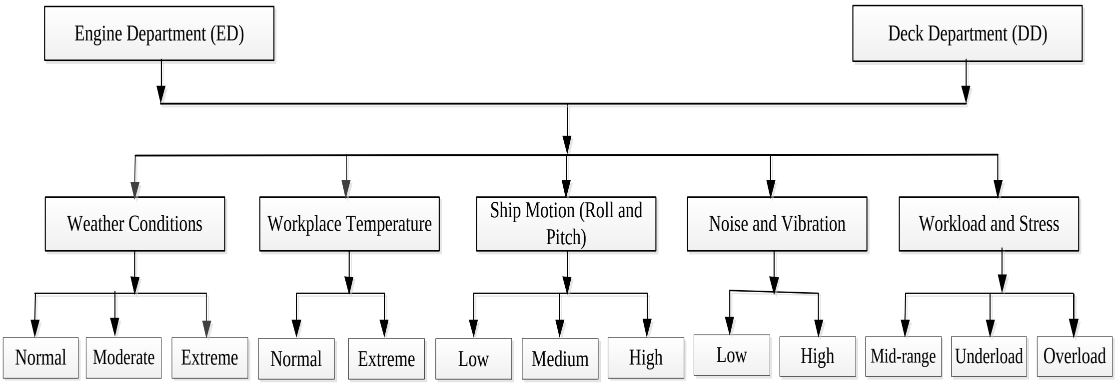


Figure 6-1: Structure of the questionnaire

These five factors and the associated sub-category may influence each other. However, in this study, interdependency of factors on seafarers' performance is not considered. For example, weather condition may have an influence on the ship motion, however, weather and ship motion are considered as individual factors in this assessment and used independently.

6.3 Selection of the Respondents

The following criteria is used to select a potential respondent: i) at least seven years of seafaring experience, ii) at least five years of experience in either maintenance department, and iii) has served or is serving as: 4th engineer, 3rd engineer, 2nd engineer or chief engineer for ED or third officer, second officer, chief officer or captain for DD. Around 400 potential respondents were identified. A SurveyMonkey link was created in order to conduct and facilitate the questionnaire survey. As this research involved human subjects, a human research ethics approval was obtained from the University of Tasmania's human research ethics committee (Ethics Ref No: H0015701). The SurveyMonkey link was sent around the world by email to a total of 400 experienced seafarers, approximately 200 in each department (i.e. engine and deck). A total of 121 responses were received from the engine department and 114 responses from the deck department. In other words, the responses rate in engine and deck departments are 60.5% and 57% respectively. To ascertain collected responses are representing the normal distribution (reflection of the majority), required sample size is estimated using Equation 6-1.

Required responses $n = \frac{Z^2\ P(1-P)}{e^2}$ **[6-1]**

$$= \frac{(1.96)^2\ (0.50)(0.50)}{(0.10)^2} = 96$$

Where, e is the margin of error (e = ± 0.10); Z is normal scale value corresponding to 95% confidence. P is the level of satisfaction; it is considered to have median value of 0.50. The number of responses collected from the ED is 121 and from DD is 114. This is far higher than the required responses. This confirms the validity of sufficient responses and assumption of normality distribution of responses.

6.4 Results and Discussion

6.4.1 Engine Department (ED)

The ED seafarers normally perform the maintenance activities in the engine room. The feedback received from the respondents to the questionnaire results are presented in Appendix 8.6. Table 8-18 illustrates the means and standard deviations of the importance score for each individual performance factor (i.e. main factors and sub-category). A series of statistical t-tests (Johnson, 2005) are conducted to compare the means in the respective responses with 95% confidence (P = 0.05). The results of the analysis are presented in Table 8-19 and Table 8-20. It is evident from the results presented in Table 8-19 that in all cases, except weather conditions versus noise and vibration, differences in the means are significant. To analyse the generality of the responses, the collected survey data is tested for normality and also applicability of t test. The normality test justifies that, data are normally distributed and thus can be generalized. Normality test plot for two sets of the questionnaire data (ship motion roll and pitch of ED and workload and stress of DD) are shown in Figure 8-1, Figure 8-2, Figure 8-3 and Figure 8-4.The plots form a plateau-like appearance rather than a straight line as some of the respondents gave a similar score to each variable. Considering the average value of each variable, results are practically direct, which demonstrates a satisfactory proposition of ordinariness (Attwood et al., 2006). The questionnaire results in this study are illustrated in a graphical form. A series of smooth curves are drawn through values representing the total numbers of responses for each importance value for each question, as presented in Figure 6-2 to Figure 6-5.

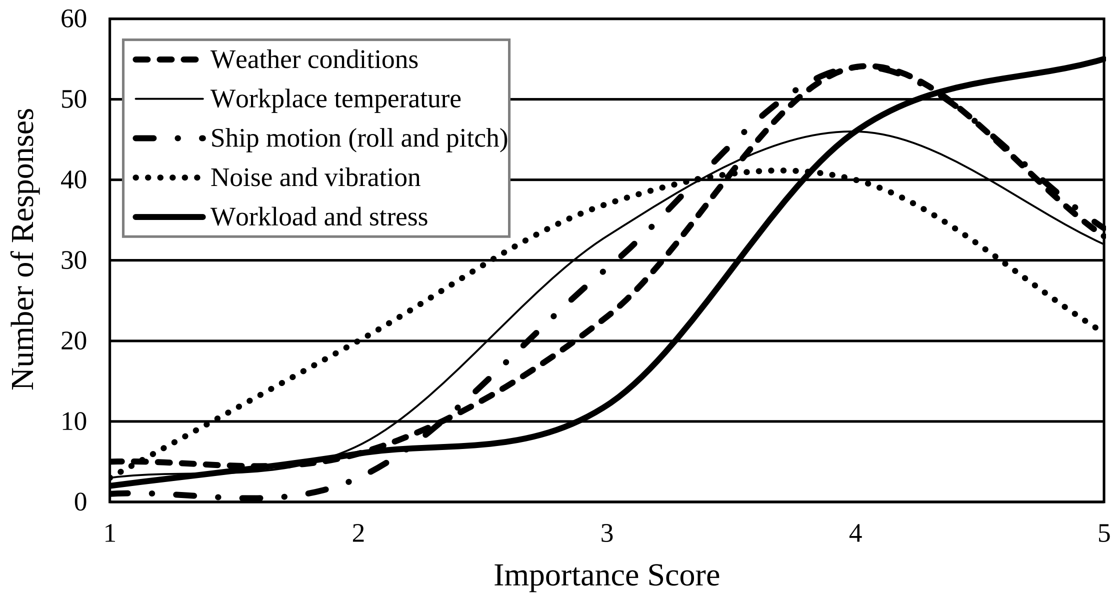


Figure 6-2: Comparative evaluation of the main factors affecting the seafarers' performance.

The responses to Question 1 in Appendix 8.5 are plotted in Figure 6-2. It is evident that workload and stress scored highest among the factors, meaning that, this factor is the highest contributor to the seafarers' performance on on-board maintenance activities. Ship motion (roll and pitch) scored next most importance followed by weather conditions and workplace temperature. A further analysis of the responses reveals that noise and vibration factor has highest standard deviation, meaning respondents' view on the importance of this factor is not uniform. Workload and stress has lowest standard deviation, meaning the majority of the respondents agree on its importance.

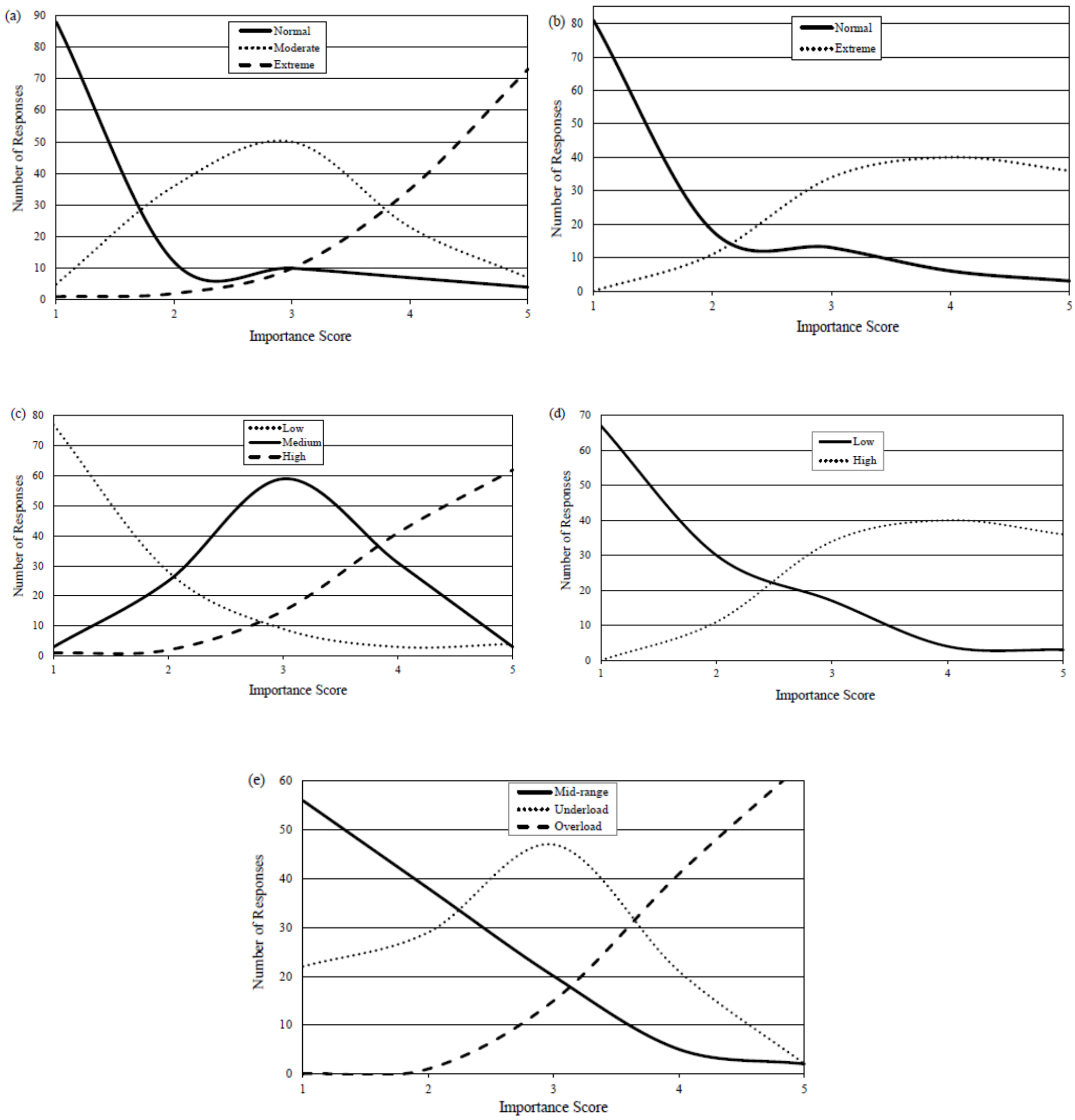


Figure 6-3: Comparison of the results: (a) normal, moderate and extreme weather conditions. (b) normal and extreme workplace temperature. (c) low, medium and high ship motion (roll and pitch). (d) low and high level of noise and vibration. (e) mid-range, underload and overload.

The responses to the second question in Appendix 8.5 are plotted in Figure 6-3(a). As expected, extreme weather condition is identified to be of highest important (having highest mean and lowest standard deviation). The t-test with 0.95 confidence interval confirms significant difference between importance of different weather conditions with extreme weather to be highest importance, while normal weather to be lowest. Responses for Question 3 in Appendix 8.5 are presented in

Figure 6-3(b). Figure 6-3(b) clearly highlights the expected outcome that extreme workplace temperature is of highest importance. The t- test further confirms the difference in the importance of each category as significant.

Figure 6-3 (c) provides responses for Question 4 in Appendix 8.5. It shows the various ranges of divergent opinions on ship motion (roll and pitch) low, medium and high. Like earlier results, the analysis of this sub-category highlights that high ship motion (roll and pitch) is highest importance. The t-test confirms the significant difference among different sub-category on ship motion (roll and pitch). Response for Question 5 in Appendix 8.5 is plotted in Figure 6-3(d). The result clearly shows that, high noise and vibration level is of greater importance and t-test further confirms the signficance difference between importance noise and viberation and other parameters.

Responses for Question 6 in Appendix 8.5 are presented in Figure 6-3(e). These results show different levels of importance among the three categories. Comparison among the mean of the responses and pairwise "t" test confirm difference as significant. Among the three categories, workload and stress overload is identified to be most important. A similar observation is noted in the study conducted by Smith et al. (2006). Smith et al. (2006) performed a study regarding seafarers' fatigue. They received 1856 seafarers' responses in this study where 36% of the seafarers' response was from the ED. They observed that workload and stress is the most important factor among the other factors (i.e. noise and vibration) leading to fatigue which influences human performance. In another survey Grech et al. (2003) studied the fatigue issue of Royal Australian Navy. They surveyed 79 crew from 6 different patrol boats. The results of the questionnaire data found that about 44% of the respondents identified workload and stress as the most important performance-affecting factor. Recently Jepsen et al. (2015) conducted a review of seafarers fatigue and found that workload and stress is the most important factor in decreasing seafarers' performance.

Ship motion (roll and pitch) was observed to be a second most important factor in this study. Stevens and Parsons (2002) conducted a survey study to ascertain the effects of ship motion on seafarers' performance. The survey results demonstrated that ship motion affected the seafarers' performance significantly and increased the chances of human error. Colwell (2005) studied the effect of ship motion on seafarers' task performance for the virtual naval platform. This study discussed the severity of seafarers' task performance problems due to ship motion and concluded that ship motion decreases seafarers' task performance hence increasing the chances of error.

Weather conditions were found to be the third most important factor affecting the seafarers' performance. Parker et al. (1997) conducted a survey of Australian seafarers and identified that extreme weather conditions decreased the seafarers' performance and increased the possibility of error. Tupper (2013a) conducted a statistical analysis and identified that numerous accidents occur due to extreme weather conditions as it decreases seafarers' performance and influences seafarer error. Christiansen and Hovmand (2017) investigated the reason for accidents in Nordic fishing vessels and concluded that the majority of accidents occurred due to extreme weather conditions.

The fourth most important factor observed was workplace temperature. A meta-analysis conducted by Pilcher et al. (2002) indicated that both extreme cold and heat have a significant impact of decreasing seafarers' performance. This is further supported by Parsons (2014). He confirmed that extreme temperature plays a significant role on seafarers' performance. Hancock et al. (2007) used Meta-analytic methods to analyse 291 collected reference data. Analyses of the data confirmed a substantial negative effect on performance associated with extreme temperature.

Noise and vibration were identified to be the least important factor among the five factors focused on within the present study. Jepsen et al. (2015) conducted a review of seafarers' fatigue and found that noise and vibration have a negative effect on seafarer's performance. Hystad and Eid (2016) collected survey data from a sample of 340 seafarers working on-board ships. The collected data justify that high level of noise and vibration do have a negative effect on seafarers' performance. However, in the present study, the noise and vibration seems to be the least important parameter.

6.4.2 Deck Department (DD)

The DD seafarers perform most of the maintenance activities on the weather deck of a ship. Responses to Question 1 in Appendix 8.5 are presented in Figure 6-4. Amongst the five factors considered in this question, workload and stress were identified to be the most important, followed by weather conditions and ship motion (roll and pitch). The pairwise t-test confirms the significance difference among most factors except the comparison between weather conditions and workplace temperature and noise and vibration. These results are similar to that observed by analysing the responses from Engineering Department. It confirms the consistency and repeatability of the survey and analysis.

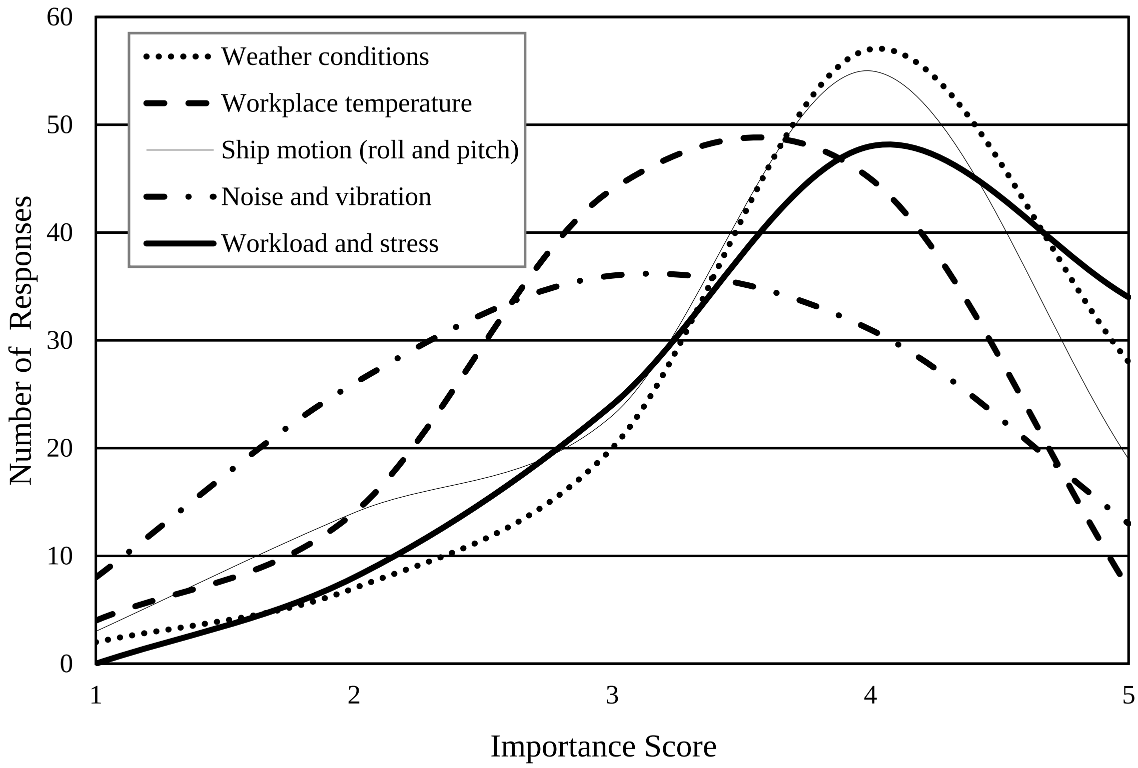


Figure 6-4: Comparative evaluation of the main factors affecting the seafarers' performance

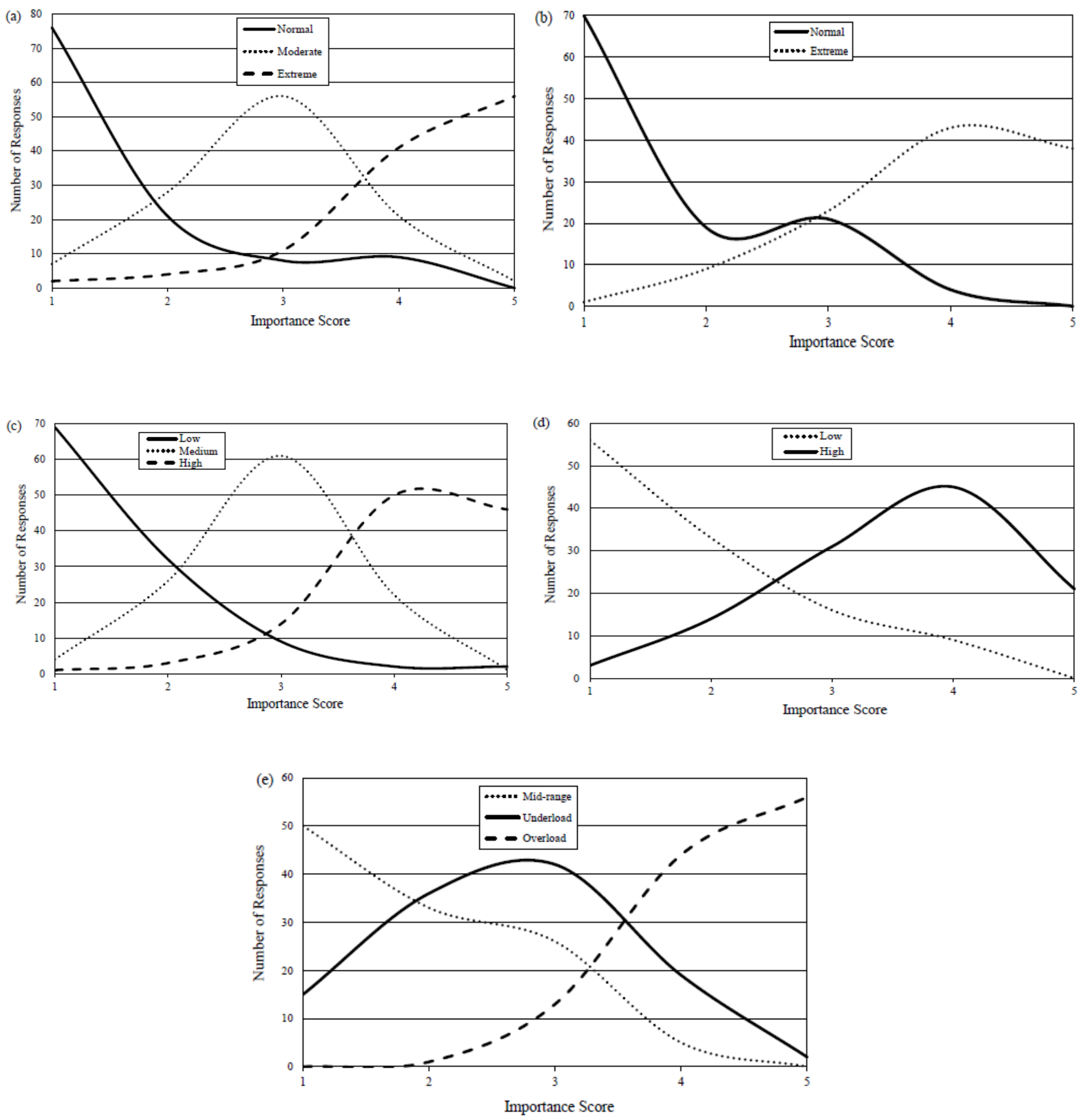


Figure 6-5. Comparison of the results: (a) normal, moderate and extreme weather conditions. (b) normal and extreme workplace temperature. (c) low, medium and high ship motion (roll and pitch). (d) low and high level of noise and vibration. (e) mid-range, underload and over workload and stress

Responses for Question 2 in Appendix 8.5 are depicted in Figure 6-5 (a). As expected, the extreme weather condition is identified to be most important when compared to moderate and normal. The result of the t-test justifies that, they have a significant difference. Response for Question 3 in Appendix 8.5 is presented in Figure 6-5 (b). These results indicate distinctly different importance level between the two sub-categories. As expected, extreme workplace temperature is identified as having higher importance than the normal. The t-test confirms that the difference is significant.

Response for Question 4 in Appendix 8.5 is plotted in Figure 6-5 (c). As observed earlier, high ship motion (roll and pitch) is identified to be of greatest importance but this is not to say medium or low ship motion (roll and pitch) are unimportant. They are also important, however of lower importance than high ship motion (roll and pitch). This is because high ship motion (roll and pitch) increases the intensity of seafarer's seasickness compared to medium or low ship motion. The t-test confirms that their differences are significant. Figure 6-5 (d) represents the response results of Question 5 in Appendix 8.5. The results indicate that respondents have ranked noise and vibration to be of high importance with a significance difference compared to low/normal category. Responses to Question 6 in Appendix 8.5 are plotted in Figure 6-5 (e).

The results highlight the variation in the responses in ranking importance level for the workload and stress sub-category. The comparison of the means highlights that workload and stress overload is most important. This observation is also confirmed using the t-test. In the response from DD, workload and stress were identified as the most important factor. This observation is supported by many studies which have focused on seafarer working on DD. Baker and Seah (2004) conducted a survey amongst U.S. coast guard and have identified that workload and stress affect seafarers' performance significantly. Further, Rengamani and Murugan (2012) conducted a questionnaire based survey and identified that work-overload and stress decrease seafarers' performance. Carotenuto et al. (2012) conducted a literature review using online databases and also evaluated the Australian Maritime Safety Authority (AMSA) survey on health, stress, and fatigue. The study confirms that the negative effect of seafarers' performance due to over workload and stress is significant.

Ship motion (roll and pitch) is observed as the second highest important factor. Stevens and Parsons (2002) conducted a survey and identified that ship motion has a negative influence on seafarers' performance. Weather conditions were found to be the third most important factor in this study. Parker et al. (1997), (Tupper, 2013a), and Christiansen and Hovmand (2017) investigations identified that extreme weather decreases seafarer's performance. Workplace temperature is identified as an important factor in this study. Previous studies by Pilcher et al. (2002) and (Parsons, 2014) confirm the decrement of seafarers' performance due to extreme temperature. Noise and vibration is observed to be the least important factor in this study while studies by Tamura et al. (1997), Jepsen et al. (2015), Hystad and Eid (2016) justify that, high level of noise and vibration have a negative effect on seafarers' performance.

6.5 Conclusions

The analysis of the data collected through a structural survey demonstrates the significance of the environmental and operational factors affecting human performance during the maintenance operation of marine systems. Workload and stress is identified to have the most substantial influence on human performance when compared to other factors. This observation is consistently confirmed by both Engineering and Deck Department respondents. Meaning that workload and stress overload has the highest influence on human error. The other considered factors are also important and the present study has demonstrated their relative importance. Among the factors considered in the present study, except for the weather conditions, all other factors have more effect on the Engine Department seafarers compared with the seafarers in the Deck Department. Because DD maintenance activities are performed on the weather deck (open place) weather conditions effect these seafarers' performance more than the ED seafarers in the engine room (closed place). The impact of over workload and stress, heavily affect the seafarers' performance during maintenance operations. This study calls for effective mechanisms to monitor and manage workload related stress on board, temperature of the workplace, and effective policy for maintenance during rough sea conditions to minimize human error and prevent accidents on-board.

7. Conclusions and Recommendations

The proposed research attempts to undertake an HRA by identifying possible failure scenarios and assesses their likelihood for the maintenance operation of marine systems. In this thesis a lot of effort has been put in to addressing the HRA for the maintenance operation of marine systems. To deal with the first objective a new methodology based on SLIM is developed to determine the HEPs during the maintenance operations of marine systems. The developed methodology is applied to the maintenance operation of a marine engine as a case study and the highest and lowest HEP-related activities are identified. Inspection and overhauls piston/piston rings have the lowest HEP value of 1.29E-04, while the fuel, lubricating oil filters pressure difference checking & renew filter elements activity has the highest HEP value of 1.67E-02. The highest HEP indicates the highest chances of accidents. The highest HEP-related maintenance activities can be to better prepare, prioritise, sort and take extra care during the maintenance and this will help to reduce the HEP. Moreover, advancements of training and experience, reduction of stress and fatigue, stabled work memory and improvement of work environment also assist to decrease the HEPs as well as shipping accidents. To address the second objective, a novel monograph is developed as easy-to-use tools to ease the HEP estimation for the maintenance operation of marine systems. The unique monograph is user-friendly and capable of estimating the HEPs instantly rather than following the step by step procedures. Developed monograph applied to the maintenance procedures of a HP fuel pump for estimating HEP. The results showed that the highest HEP value is 1.40E-02, which is for the inspection of fuel injectors, renewing nozzles and testing. This well-defined monograph will help the chief engineer or captain to quickly estimate human error during the marine operations. This monograph could also be applied as guidance for ship owners, operators, masters and classification societies to better prepare, prioritise and sort the maintenance activities for the safe and reliable on-board maintenance operations. It can serve as a helpful tool to reduce the potential occurrence of accidents. The third objective is achieved by developing an HRA technique for estimating the HEPs during the maintenance procedures of marine operations. This developed technique fulfils the IMO recommendation implementing HEART for HRA. The newly developed technique is applied to estimate the HEP for the maintenance procedures of a marine engine exhaust gas turbocharger as a case study. Based on the selected scenario of marine environmental and operational conditions, HEP are estimated for each sub-activity presenting highest and lowest probability of human errors. The results of the case study demonstrate that estimated HEPs for the maintenance procedures of marine engine exhaust gas turbocharger sub-activities are in the range of 1.16E-04 and 1.25E-01. Among the considered sub-activities, highest probability of error is found to be checking the clearances after an overhaul and lowest HEP is found to be for cleaning air filter.

The fourth objective is attained by developing an HEP assessment technique for the maintenance activities of marine systems based on an advanced probabilistic technique named BN. This developed technique has a dynamic updating capability which will help to estimate HEP instantly when new information is available. The developed methodology is applied to estimate HEP in various real life scenarios as case studies. The case study results identified that in scenario 2, HEPs are increased for ED and DD both department's maintenance activities due to changing the workplace temperature from normal to extreme and level of noise and vibration from low to high. In seafarers category "A", HEP increased from 2.98E-04 to 2.40E-01, category "B" 1.18E-03 to 2.41E-01, category "C" 2.65E-03 to 4.02E-01 and category "D" 4.67E-03 to 4.03E-01 due to changing the scenario 1 to 2.

The fifth objective is achieved by assessing the data from surveying and conducting various statistical tests. According to the collected survey data, over workload and stress found to be the most influential factors on seafarers performance in the range of 5 (in 1-5 likert scale).

The final objective is achieved by applying the developed methodology and tools to the real life maintenance activities via different case studies.

7.1 Recommendations

The present work attempts to introduce new methodologies to assess the HEPs during the maintenance operations of marine systems. This study can be further extended as follows:

(i) Organizational factors should consider further study for more accurate HEP estimation;

(ii) Dynamic Bayesian Network (DBN) is capable of estimating HEP over time. Therefore, further study should focus on developing methodology based on DBN.

(iii) Development of HRA methodology and tools specific to the ship type/ size could be helpful in obtaining more accurate HEP estimation and is a recommendation for future study.

8. Appendices

8.1 Probabilities for the maintenance activities of marine operations

Prior probabilities for the maintenance activities of marine operations see Table 8-1 and Table 8-2.

Table 8-1: Prior probability for internal factors

Category	**Training**		**Experience**		**Fatigue**	
	Low	High	Low	High	Low	High
A	0.01	0.99	0.01	0.99	0.99	0.01
B	0.02	0.98	0.02	0.98	0.98	0.02
C	0.03	0.97	0.03	0.97	0.97	0.03
D	0.04	0.96	0.04	0.96	0.96	0.04

Table 8-2: Prior probability for external factors

Parent nodes	**States**			**External factors**
	Normal	Moderate	Extreme	
Weather conditions	0.90	0.07	0.03	Environmental
Workplace temperature	0.95	-	0.05	
Ship Motion (roll and pitch)	Low	Medium	High	Operational
	0.92	0.06	0.02	
Noise and vibration	0.97	-	0.03	
Workload and stress	Mid-range	Underload	Overload	
	0.91	0.06	0.03	

8.2 CPT for the environmental and operational factors of ED

For the environmental and operational factors CPT of ED see Table 8-3 to Table 8-10.

Table 8-3: CPT for environmental factors (category-A)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	0.80	0.60	1.00
Environmental factor (good)	1.00	0.20	0.20	0.20	0.40	0.00

Table 8-4: CPT for environmental factors (category-B)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	0.80	0.60	1.00
Environmental factor (good)	1.00	0.20	0.20	0.20	0.40	0.00

Table 8-5: CPT for environmental factors (category-C)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	0.80	0.60	1.00
Environmental factor (good)	1.00	0.20	0.20	0.20	0.40	0.00

Table 8-6: CPT for environmental factors (category-D)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	1.00	0.80	1.00
Environmental factor (good)	1.00	0.20	0.20	0.00	0.20	0.00

Table 8-7: CPT for operational factors (category-A)

Ship Motion (Roll and Pitch)	Low						Medium						High					
Workload and Stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and Vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.60	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00
Operational factor (good)	1.00	0.40	1.00	0.40	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00

Table 8-8: CPT for operational factors (category-B)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.60	0.80	0.80	0.60	1.00	0.60	1.00	0.80	0.80	0.60	1.00	0.60	1.00	0.60	1.00
Operational factor (good)	1.00	0.40	1.00	0.4	0.20	0.20	0.40	0.00	0.40	0.00	0.20	0.20	0.40	0.00	0.40	0.00	0.40	0.00

Table 8-9: CPT for operational factors (category-C)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	1.00	0.00	1.00	1.00	1.00	0.00	0.80	0.00	0.80	0.80	1.00	0.80	1.00	0.80	1.00	1.00	1.00
Operational factor (good)	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.20	1.00	0.20	0.20	0.00	0.20	0.00	0.20	0.00	0.00	0.00

Table 8-10: CPT for operational factors (category-D)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	1.00	0.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Operational factor (good)	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

8.3 Operational factors CPT for DD

For the operational factors CPT of DD see Table 8-11 to

Table **8-14**.

Table 8-11: CPT for operational factors (category-A)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.60	0.60	0.80	0.60	0.80	0.40	0.80	0.60	1.00	0.40	0.80	0.40	0.80	0.40	0.80
Operational factor (good)	1.00	0.40	1.00	0.40	0.40	0.20	0.40	0.20	0.60	0.20	0.40	0.00	0.60	0.20	0.60	0.20	0.60	0.20

Table 8-12: CPT for operational factors (category-B)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.80	0.60	1.00	0.60	1.00	0.80	0.80	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00
Operational factor (good)	1.00	0.40	1.00	0.20	0.40	0.00	0.40	0.00	0.20	0.20	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00

Table 8-13: CPT for operational factors (category-C)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00
Operational factor (good)	1.00	0.40	1.00	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00

Table 8-14: CPT for operational factors (category-D)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.80	0.00	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00
Operational factor (good)	1.00	0.20	1.00	0.00	0.00	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00

8.4 CPT for internal, external factor and HEP for the maintenance activities

For the internal, external factors and HEP for the maintenance activities CPT see the Table 8-15 to Table 8-17.

Table 8-15: CPT for seafarers' internal factors

Training	Low				High			
Experience	Low		High		Low		High	
Fatigue	Low	High	Low	High	Low	High	Low	High
Seafarers' internal factors (poor)	1.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00
Seafarers' internal factors (good)	0.00	0.00	1.00	0.00	1.00	0.00	1.00	1.00

Table 8-16: CPT for seafarers' external factors

Environmental factors	Bad		Good	
Operational factors	Bad	Good	Bad	Good
Seafarers' external factors (poor)	1.00	0.00	0.00	0.00
Seafarers' external factors (good)	0.00	1.00	1.00	1.00

Table 8-17: CPT for HEP of the maintenance activities of marine operations

Seafarers internal factors	Bad		Good	
Seafarers external factors	Bad	Good	Bad	Good
Maintenance activities of marine operations (failure)	1.00	0.50	1.00	0.00
Maintenance activities of marine operations (success)	0.00	0.50	0.00	1.00

8.5 The Questionnaire

A questionnaire was developed to investigate the relative importance of seafarers' performance affecting factors during maintenance operation of marine system. There are six questions in total in the questionnaire. The responses to these questions are adopted based on using five likert scales.

Question 1 seeks response of the operating condition on the seafarer's performance during maintenance operation of marine systems.

Questions 2 is meant to seek feedback on the relative importance of the sub-categories of seafarers' performance affecting factors. This question is developed according to the North Atlantic Treaty Organization sea state definitions adopted from Ross (2009). Sea state 0-3, wave height 0-1.25 m and wind speed 0-16 KT is classified as a "normal" weather condition. Likewise sea state 4-6, wave height 1.25-6 m and wind speed 17-47 KT is classified as "moderate" weather condition. Finally, sea state 7-9, wave height of 6-14 m and wind speed of 48-63 KT or more is classified as "extreme" weather conditions.

Question 3 enquires the importance of work place temperature on seafarer's performance during maintenance operation of marine systems. This question is developed considering temperature around 20°C as "normal" for human performance reported by researchers (Eraut, 2007; Pilcher et al., 2002). On the other hand, ambient temperatures higher or lower than a human being's comfort zone are considered as "extreme" temperature, 32.2°C and above is hot, and 10°C and below is cold (Pilcher et al., 2002).

Question 4 seeks feedback on how important is ship motion (roll and pitch) with regards to seafarer's performance during maintenance operation of marine systems. This questionnaire is developed according to the motion limits for safe and effective seafarers performance which is adopted from Ross (2009). "Low" ship motion is categorized at <4º roll angle and <1.5º pitch angle. On the other hand, 4-10º roll angle and 1.5-5º pitch angle is categorized as "medium" ship motion. Finally, >10º roll angle and >5º pitch angle is categorized as "high" ship motion.

Question 5 enquires importance of noise and vibration on seafarer's performance during maintenance operation of marine systems. This questionnaire is developed according to the range of noise and vibration level and adopted from Turan et al. (2011). Noise level of 110 dB (A) or less and vibration level less than 1 Root Mean Square (RMS) is considered as “low”. However, the noise level higher than 110 dB (A) and the vibration level more than 1 RMS is considered as “high”.

Question 6 seeks response on how important is workload and stress on seafarer’s performance during maintenance operation of marine systems? This questionnaire is developed considering previous research (Ross, 2009), workload and stress is categorized as mid-range underload and overload. A low work load within an available time together with a seafarers’ high skill level for a very low-level task, is categorized as an “underload”. Similarly, too much work to be done in a limited time is categorized as “overload”.

The response is sought on five point Likert scale based on ratings 1 to 5 for each specific question (Trochim and Donnelly, 2001). Rating 1 denotes the lowest and 5 has the highest effect on seafarers’ performance.

8.6 Questionnaire analysis

The analysis of the questionnaire response is presented in Table 8-18, Table 8-19 and Table 8-20.

Table 8-18: Means and standard deviations of the results

Parameter	**Mean Value (Rating)**		**Standard Deviation**	
	Engine department (ED)	**Deck department (DD)**	**Engine department (ED)**	**Deck department (DD)**
Weather conditions	4.00	4.00	1.01	0.90
Workplace Temperature	4.00	4.00	0.98	0.89
Ship Motion (Roll and Pitch)	4.00	4.00	0.83	0.98
Noise and Vibration	4.00	4.00	1.04	1.10
Workload and Stress	5.00	4.00	0.93	0.89
Weather conditions				
Normal	2.00	2.00	1.07	0.93
Moderate	3.00	3.00	0.94	0.85
Extreme	5.00	5.00	0.78	0.90
Workplace Temperature				
Normal	2.00	2.00	1.02	0.90
Extreme	4.00	4.00	0.96	0.96

Ship Motion (Roll and Pitch)				
Low	2.00	2.00	0.97	0.85
Medium	3.00	3.00	0.81	0.77
High	5.00	5.00	0.82	0.82
Noise and Vibration				
Low	2.00	2.00	0.98	0.95
High	4.00	4.00	1.03	1.00
Workload and Stress				
Mid-range	2.00	2.00	0.96	0.91
Underload	3.00	3.00	1.02	0.97
Overload	5.00	5.00	0.73	0.71

Table 8-19: T- test results for different factors and sub-categories

"t" tests factors	**Significant? (P > 0.05)**	
	ED	**DD**
Weather conditions vs. workplace temperature	Yes	No
Weather conditions vs. ship motion (roll and pitch)	Yes	No
Weather conditions vs. noise and vibration	No	No
Weather conditions vs. workload and stress	Yes	Yes
Workplace temperature vs. ship motion (roll and pitch)	Yes	No
Workplace temperature vs. noise and vibration	No	Yes
Workplace temperature vs. workload and stress	No	No
Ship motion (roll and pitch) vs. noise and vibration	No	No
Ship motion (roll and pitch) vs. workload and stress	No	No
Noise and vibration vs. workload and stress	No	No
Normal vs. moderate	No	No
Normal vs. extreme	No	No
Moderate vs. extreme	No	No
Normal vs. extreme	No	No
Low vs. medium	No	No
Low vs. high	No	No
Medium vs. high	No	No
Low vs. high	No	No
Mid-range vs. underload	No	No
Mid-range vs. overload	No	No
Underload vs. overload	No	No

Table 8-20: T- test results for ED and DD

"t" tests factors	**Significant? (P > 0.05)**
Weather conditions ED vs. DD	Yes
Workplace temperature ED vs. DD	No
Ship motion (roll and pitch) ED vs. DD	No

Noise and vibration ED vs. DD	No
Workload and stress ED vs. DD	No
Normal ED vs. DD	Yes
Moderate ED vs. DD	Yes
Extreme ED vs. DD	Yes
Normal ED vs. DD	Yes
Extreme ED vs DD	Yes
Low ED vs. DD	Yes
Medium ED vs. DD	Yes
High ED vs. DD	Yes
Low ED vs. DD	Yes
High ED vs. DD	Yes
Mid-range ED vs. DD	Yes
Underload ED vs. DD	Yes
Overload ED vs. DD	Yes

8.7 Sample Normality tests

For normality evaluation see Figure 8-1, Figure 8-2, Figure 8-3 and Figure 8-4.

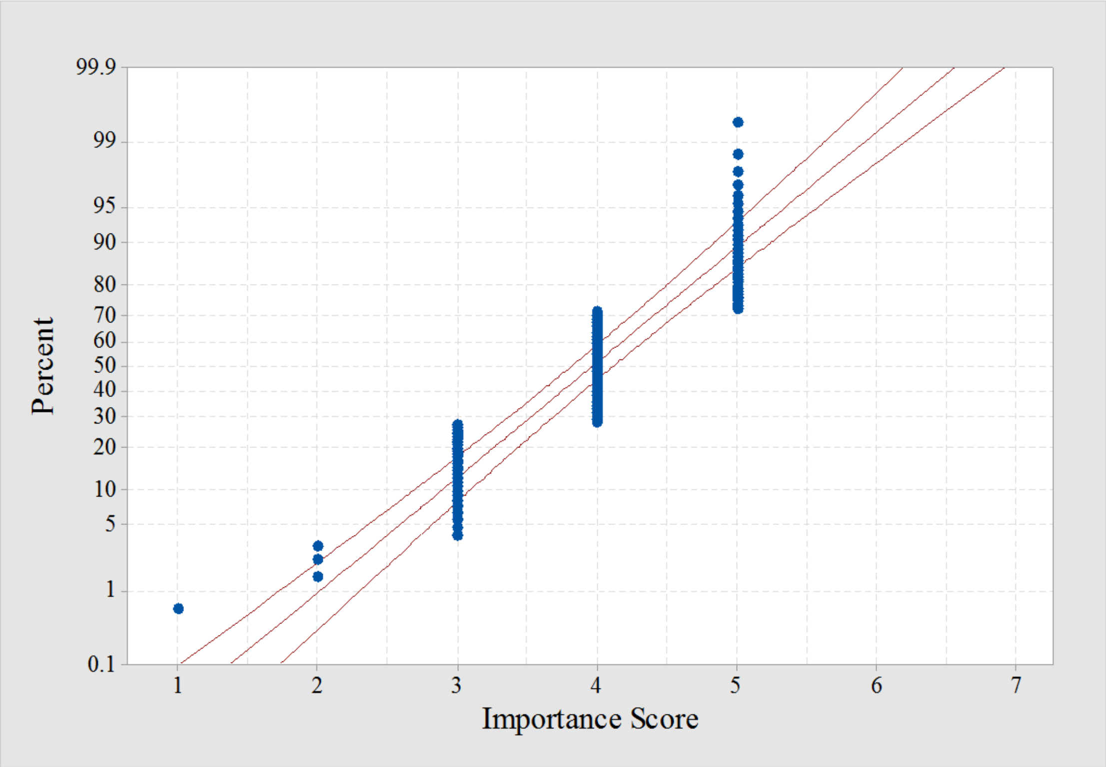


Figure 8-1: Normality test for ship motion (roll and pitch) of ED

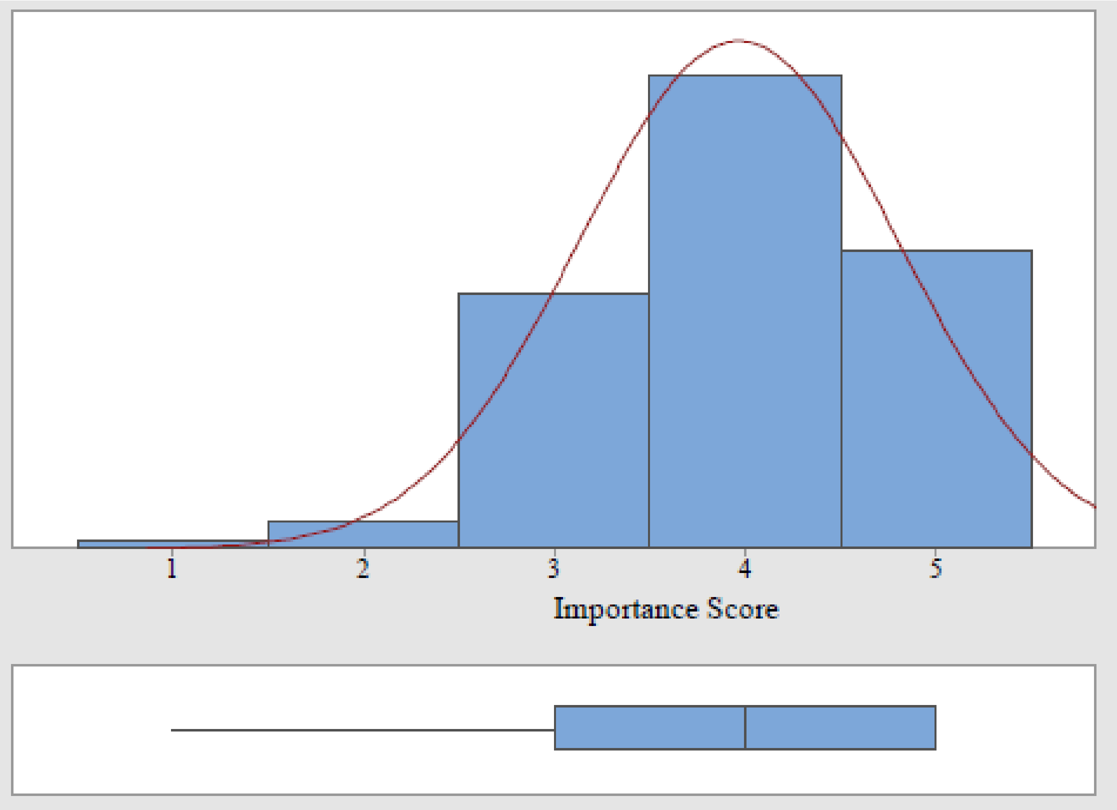


Figure 8-2: Anderson-darling normality test summary report for ship motion (roll and pitch) of ED

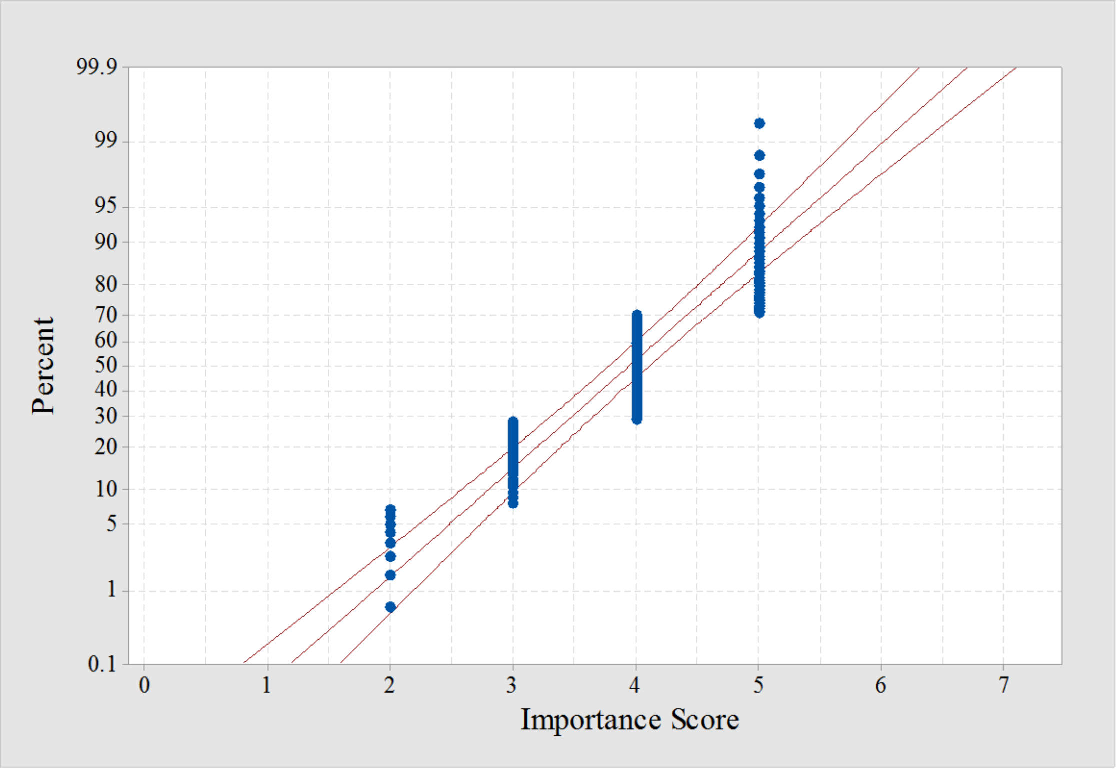


Figure 8-3: Normality test for workload and stress of DD

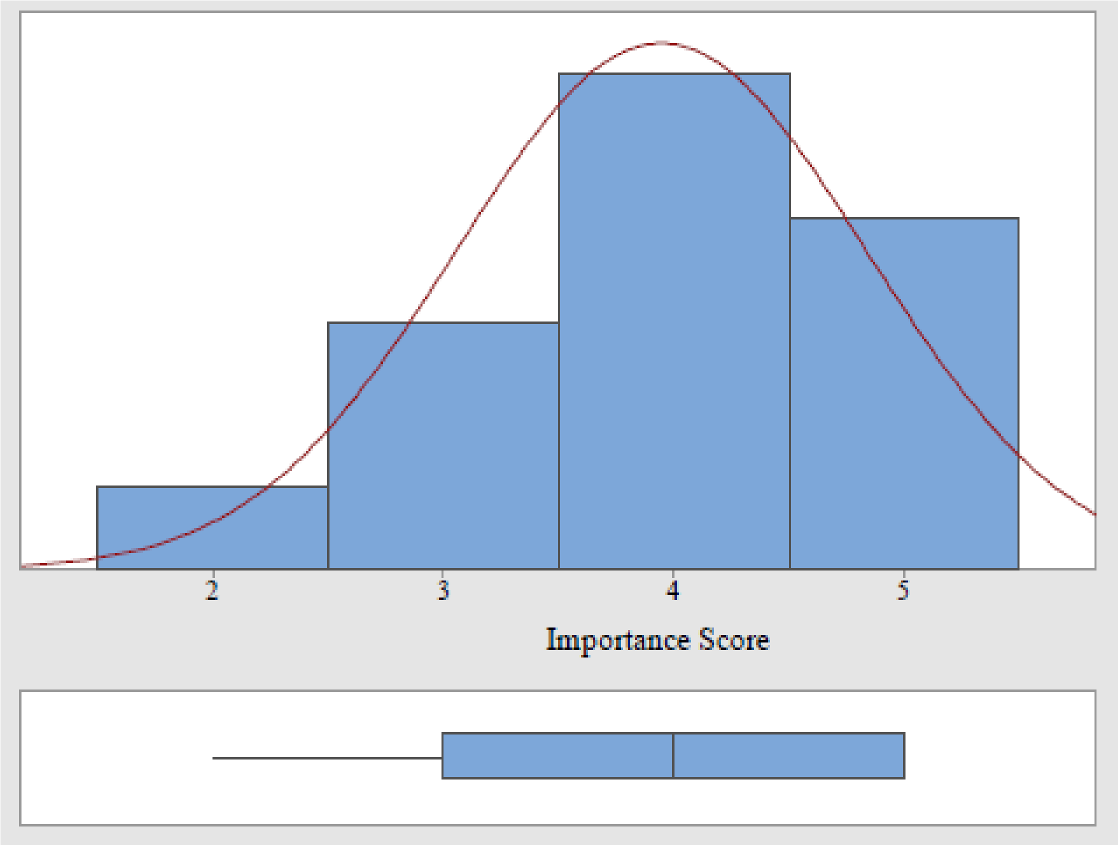


Figure 8-4: Anderson-darling normality test summary report for workload and stress of DD

8.7 Collected raw data for ED main factors

Respondent	Weather conditions	Workplace Temperature	Ship Motion (Roll and Pitch)	Noise and Vibration	Workload and Stress
1	4	1	4	3	3
2	5	5	5	5	5
3	4	3	3	3	3
4	5	5	5	5	4
5	3	5	5	4	4
6	4	5	5	5	5
7	5	4	5	4	5
8	5	5	5	2	2
9	5	5	5	4	5
10	5	1	4	4	4
11	4	4	5	5	4
12	5	4	5	5	4
13	5	3	4	3	4
14	5	4	5	2	5
15	5	5	5	5	4
16	4	4	4	3	5
17	5	5	5	5	5
18	3	4	4	5	5
19	5	4	5	4	5
20	4	5	4	4	5
21	4	4	5	5	5
22	5	4	5	5	4
23	4	4	5	4	4
24	1	3	1	3	4
25	3	4	3	2	5
26	3	5	3	2	2
27	4	4	4	2	5
28	4	5	4	3	4
29	3	4	4	4	4
30	5	5	5	5	5
31	2	4	4	4	4
32	4	5	4	4	4
33	5	3	4	3	3
34	5	5	5	5	5
35	5	3	4	4	5
36	4	5	5	4	5
37	5	3	4	4	4

38	5	2	4	3	4
39	5	4	5	3	4
40	3	3	3	3	3
41	2	4	4	4	5
42	3	4	4	4	4
43	4	4	4	2	5
44	1	3	3	4	5
45	3	3	5	3	4
46	3	2	2	2	2
47	3	3	3	3	3
48	3	4	4	4	5
49	5	5	5	5	5
50	5	5	5	5	5
51	5	4	4	4	5
52	1	3	2	3	1
53	4	3	5	3	5
54	5	5	4	4	4
55	4	2	3	2	2
56	4	4	3	3	4
57	4	5	4	3	4
58	3	3	4	2	3
59	3	5	4	1	4
60	5	5	5	5	5
61	4	4	4	4	5
62	4	3	4	4	4
63	4	3	4	4	5
64	3	2	3	2	4
65	4	4	3	2	4
66	5	4	4	2	2
67	5	5	5	4	5
68	5	3	4	4	5
69	3	4	4	4	4
70	2	2	3	3	4
71	5	5	4	4	5
72	4	5	5	4	5
73	4	4	3	2	3
74	3	2	4	3	4
75	4	5	4	3	4
76	4	4	5	4	5
77	4	4	4	3	4
78	3	3	3	2	5

79	4	4	4	3	4
80	2	3	3	1	4
81	4	4	3	5	5
82	3	4	3	3	4
83	4	4	3	3	4
84	4	5	4	4	5
85	4	5	4	3	5
86	4	1	3	2	1
87	2	3	4	1	5
88	4	5	5	2	3
89	3	4	4	5	2
90	4	3	3	2	3
91	4	3	4	3	3
92	4	3	3	3	4
93	5	5	4	3	4
94	4	4	3	3	4
95	5	3	5	3	5
96	5	2	4	4	4
97	4	3	4	3	4
98	4	3	5	2	4
99	4	4	4	3	5
100	1	3	3	4	5
101	4	5	3	4	5
102	4	3	4	4	5
103	3	4	5	5	5
104	3	4	5	5	5
105	4	4	4	2	4
106	4	4	3	4	5
107	4	4	4	5	4
108	4	3	4	3	4
109	5	3	4	3	4
110	4	3	3	4	5
111	4	4	4	3	5
112	1	3	3	4	5
113	4	5	3	4	5
114	4	3	4	4	5
115	3	4	5	5	5
116	4	4	4	2	4
117	4	4	3	4	5
118	4	3	4	3	3
119	3	4	2	4	5

120	4	5	3	3	3
121	2	4	4	3	5

8.8 Collected raw data for ED (sub-category)

Respondent	Weather conditions			Workplace Temperature		Ship Motion (Roll and Pitch)			Noise and Vibration		Workload and Stress		
	Normal	Moderate	Extreme	Normal	Extreme	Low	Medium	High	Low	High	Mid-range	Underload	Overload
1	1	2	4	1	2	1	2	4	1	2	1	1	2
2	1	2	5	1	5	1	3	5	1	5	1	2	5
3	1	2	4	1	3	1	2	4	1	3	1	1	3
4	4	5	5	5	5	3	3	5	4	4	3	3	3
5	3	3	4	4	4	1	1	4	3	1	4	2	4
6	1	2	5	1	5	2	3	5	1	5	1	1	5
7	1	3	5	1	4	2	4	5	2	4	1	2	5
8	1	5	3	3	5	1	5	3	1	3	1	1	3
9	1	4	5	1	5	1	3	5	1	5	1	2	5
10	2	3	5	1	5	1	3	5	1	4	1	3	5
11	4	3	5	2	2	1	3	5	1	5	2	3	5
12	3	4	5	3	4	4	3	5	4	5	4	3	5
13	5	4	5	5	5	5	4	5	3	5	3	1	3
14	5	4	5	3	4	5	3	5	5	5	4	2	5
15	4	4	5	4	5	3	3	5	3	4	3	4	5
16	1	2	5	2	5	1	3	4	1	3	5	4	5
17	5	5	5	5	5	5	5	5	5	5	5	5	5
18	1	4	5	3	5	4	4	5	2	5	3	3	5
19	5	5	5	4	5	4	4	4	4	4	4	3	4
20	1	3	5	1	5	1	3	5	2	5	1	1	5

21	1	4	5	1	4	1	4	5	3	5	1	1	5
22	2	2	4	2	5	2	2	4	2	2	2	3	5
23	1	4	5	1	4	5	4	5	5	5	1	2	4
24	4	4	4	4	4	3	3	5	3	4	3	2	5
25	1	3	5	1	4	1	3	5	1	5	2	4	5
26	1	3	5	1	5	1	3	5	1	3	1	3	5
27	3	5	5	2	5	1	3	5	1	3	1	3	5
28	1	3	3	1	3	1	1	3	1	1	1	2	3
29	1	3	5	1	3	1	2	2	1	3	1	4	5
30	1	3	4	3	4	2	3	3	3	4	3	3	3
31	3	4	5	3	5	2	4	5	3	5	2	3	4
32	3	5	5	3	5	2	4	5	3	5	2	3	4
33	1	3	4	1	4	1	3	5	1	4	2	4	5
34	2	4	5	1	2	2	3	5	2	2	1	1	4
35	1	3	5	4	5	1	4	5	3	5	3	4	5
36	3	4	5	2	5	3	4	5	2	4	3	2	5
37	2	3	5	1	3	2	3	4	1	4	2	3	4
38	3	3	3	3	5	3	3	5	3	5	3	4	5
39	1	2	5	1	5	1	3	5	2	5	3	2	5
40	1	2	1	2	2	1	3	3	3	3	3	3	3
41	1	4	4	1	5	1	4	4	1	4	3	4	5
42	2	4	5	2	4	2	4	5	2	4	2	3	5
43	2	3	5	3	2	2	3	5	2	4	2	3	4
44	2	3	5	3	5	2	3	5	2	4	2	3	4
45	1	2	3	1	3	1	3	3	1	3	1	3	3
46	1	2	2	2	3	2	2	2	1	2	1	2	3

47	1	3	4	1	4	1	3	4	1	4	1	2	4
48	1	3	4	1	4	3	4	5	3	4	3	3	5
49	1	3	5	1	5	1	3	4	1	5	1	4	5
50	1	3	5	1	4	1	3	5	1	5	3	4	5
51	1	3	5	2	4	2	2	4	1	5	2	3	5
52	3	4	5	2	5	1	4	5	1	4	1	3	5
53	1	3	5	1	3	1	3	5	1	2	1	3	4
54	3	4	5	1	3	3	4	5	4	5	4	4	5
55	3	3	4	1	2	1	3	4	3	5	2	3	4
56	1	3	5	1	4	1	3	4	3	4	1	3	5
57	4	3	4	4	4	1	5	5	1	3	1	3	4
58	2	3	4	3	3	1	4	4	1	4	1	3	4
59	1	2	5	1	5	1	2	5	1	3	1	2	5
60	1	2	4	1	4	1	3	1	3	4	1	3	4
61	1	1	4	1	3	1	1	3	1	4	1	2	4
62	1	1	4	1	4	2	4	5	1	4	2	1	3
63	1	3	5	2	4	1	2	3	2	4	1	3	4
64	1	2	5	1	3	1	2	4	1	2	1	1	4
65	1	1	2	1	4	1	2	4	1	2	1	2	4
66	1	4	5	1	4	1	2	3	1	2	1	2	4
67	1	2	5	1	5	1	3	5	2	4	2	5	5
68	1	2	4	1	3	1	3	4	2	4	2	3	5
69	1	2	5	1	5	1	4	5	2	5	1	2	4
70	1	3	4	1	3	1	3	4	1	4	2	3	4
71	1	3	5	1	4	2	3	5	2	4	2	3	5
72	1	3	5	1	5	2	3	4	3	5	3	3	5

73	1	2	3	1	3	1	2	3	2	4	1	2	4
74	1	3	4	1	2	2	3	4	1	3	1	3	4
75	1	3	5	2	5	1	4	5	3	4	3	4	5
76	1	2	3	1	2	1	3	4	1	3	2	3	3
77	1	2	4	1	4	1	2	4	1	4	1	3	4
78	4	3	5	1	3	1	3	5	1	4	2	3	5
79	1	4	5	1	4	1	3	4	1	3	1	3	4
80	1	3	4	1	3	1	3	5	1	2	1	2	4
81	1	3	3	3	4	2	3	4	1	3	2	1	4
82	1	2	5	2	4	1	2	4	1	4	2	1	5
83	1	3	5	1	3	1	4	4	1	3	1	4	5
84	2	3	5	1	5	2	4	5	2	4	2	2	5
85	1	2	4	1	4	1	2	3	1	2	1	2	4
86	1	4	5	2	5	1	2	4	1	5	2	2	4
87	1	5	5	1	4	2	4	5	1	2	3	2	5
88	2	3	5	2	4	2	3	5	2	4	2	3	5
89	1	2	4	1	3	1	2	3	1	3	1	2	3
90	1	2	4	1	4	1	3	4	1	2	1	1	5
91	1	4	4	1	2	1	3	4	1	2	1	1	3
92	1	3	4	1	4	1	3	4	1	3	2	1	4
93	1	3	4	1	5	2	3	4	2	3	2	4	4
94	1	3	4	1	4	1	3	3	1	3	1	2	4
95	1	3	5	1	3	1	3	5	1	4	1	1	4
96	1	2	5	1	2	1	2	4	1	5	1	4	5
97	1	3	3	1	3	1	3	3	1	3	1	3	3
98	1	2	5	1	3	1	3	5	1	3	1	1	5

99	1	1	3	1	3	1	2	4	1	2	2	2	5
100	1	2	4	1	3	1	2	4	1	4	2	1	5
101	1	2	5	1	3	3	4	5	1	4	1	3	4
102	2	4	5	2	4	2	4	5	2	4	3	4	5
103	1	3	5	1	3	2	3	5	2	5	2	1	5
104	1	3	5	1	3	2	3	5	2	5	2	1	5
105	1	2	5	1	4	1	4	5	2	3	2	3	5
106	1	2	5	1	3	1	3	4	1	4	1	4	5
107	1	2	4	1	3	1	2	4	1	3	1	3	4
108	1	3	5	1	4	1	4	5	1	4	1	3	4
109	1	2	3	1	2	1	3	4	1	2	1	3	4
110	1	3	4	1	3	1	2	3	1	3	1	2	3
111	1	1	4	1	3	1	2	4	1	2	2	2	5
112	1	2	4	1	3	1	2	4	1	4	2	1	5
113	1	2	5	1	3	3	4	5	2	4	2	3	4
114	2	4	5	2	4	2	4	5	2	4	3	4	5
115	1	3	5	1	3	2	3	5	2	5	2	1	5
116	1	2	5	1	4	1	4	5	2	3	2	3	5
117	1	4	5	1	3	1	4	4	2	4	3	4	5
118	4	3	5	2	4	2	4	5	2	4	2	3	4
119	1	2	5	3	5	1	2	4	2	4	2	4	5
120	1	2	4	1	5	1	3	5	1	3	1	2	4
121	1	3	4	1	4	1	3	3	1	3	1	4	5

8.9 Collected raw data for DD main factors

Respondent	Weather conditions	Workplace Temperature	Ship Motion (Roll and Pitch)	Noise and Vibration	Workload and Stress
1	4	3	4	1	3
2	4	3	4	3	2
3	5	3	5	3	5
4	4	4	4	4	4
5	5	4	3	4	4
6	4	3	4	4	5
7	4	4	4	4	5
8	3	4	4	3	4
9	3	3	3	3	4
10	4	3	4	2	4
11	4	4	4	3	4
12	4	4	4	4	5
13	4	4	3	3	3
14	4	4	4	4	4
15	4	4	4	4	5
16	4	3	4	4	3
17	4	2	4	4	3
18	2	2	4	2	4
19	5	3	4	3	2
20	3	3	4	4	4
21	3	3	5	5	4
22	4	4	4	4	4
23	5	4	5	5	4
24	4	3	2	2	5
25	4	3	3	3	3
26	4	4	4	2	3
27	5	3	5	3	4
28	4	4	3	4	3
29	3	5	5	4	3
30	4	3	3	3	5
31	5	3	2	1	4
32	2	3	2	1	5
33	2	3	1	2	3
34	4	4	3	2	3
35	5	3	4	1	3
36	4	2	4	2	5

37	3	3	4	3	5
38	4	5	3	3	3
39	4	4	4	4	4
40	4	4	4	4	4
41	3	4	4	3	4
42	5	4	4	3	3
43	4	3	3	2	3
44	4	3	4	4	5
45	2	1	1	2	2
46	3	3	3	3	3
47	5	4	5	2	2
48	4	2	4	2	3
49	5	4	2	3	5
50	4	4	2	2	2
51	4	1	3	2	5
52	5	4	4	4	4
53	3	2	4	3	4
54	3	3	3	3	3
55	2	3	2	3	4
56	4	3	4	4	4
57	5	4	5	4	5
58	3	1	2	1	3
59	4	3	4	5	4
60	1	4	2	3	2
61	5	5	5	3	4
62	5	3	5	5	3
63	4	3	4	3	4
64	4	3	4	3	4
65	3	3	3	3	3
66	4	3	2	1	5
67	5	4	4	5	4
68	4	4	4	2	3
69	4	3	4	3	5
70	5	4	4	4	5
71	5	4	5	5	5
72	3	2	5	5	5
73	4	3	2	2	4
74	4	4	5	4	4
75	4	2	4	3	2
76	4	3	4	4	5
77	3	4	3	5	4
78	4	3	5	2	4
79	3	3	4	2	5

80	4	4	3	3	4
81	4	4	3	2	5
82	5	1	3	1	2
83	3	2	4	3	4
84	4	4	4	4	4
85	4	4	2	5	5
86	4	4	4	4	4
87	4	3	4	4	5
88	3	2	3	3	4
89	5	5	5	4	5
90	2	2	3	3	4
91	5	2	5	3	4
92	5	4	5	5	4
93	4	2	4	2	5
94	2	3	2	3	3
95	4	3	2	2	4
96	5	3	3	2	3
97	1	2	1	2	5
98	5	4	4	3	4
99	4	4	4	4	4
100	4	4	3	2	5
101	4	5	5	5	5
102	5	5	4	2	4
103	3	4	3	2	4
104	4	3	4	4	5
105	5	5	5	5	5
106	4	3	4	4	5
107	3	3	3	4	4
108	5	4	4	4	5
109	4	4	4	3	4
110	5	4	4	3	3
111	4	4	4	5	4
112	3	2	2	1	4
113	4	3	3	3	5
114	5	4	4	2	4

8.10 Collected raw data for DD (Sub-category)

Respondent	Weather Conditions			Workplace Temperature		Ship Motion (Roll and Pitch)			Noise and Vibration		Workload and Stress		
	Normal	Moderate	Extreme	Normal	High	Low	Medium	High	Low	High	Mid-range	Underload	Overload
1	3	3	5	3	4	3	3	5	2	3	2	2	4
2	2	3	4	3	3	2	3	3	4	4	2	2	4
3	4	3	5	2	4	2	2	4	2	4	2	3	5
4	3	4	5	3	5	3	4	5	3	5	1	2	5
5	2	2	3	1	3	1	4	5	3	4	3	4	5
6	1	3	4	1	3	1	3	4	1	1	1	1	5
7	1	1	5	1	3	1	2	4	1	4	1	1	5
8	3	3	3	3	4	3	3	3	2	2	3	2	3
9	2	4	5	3	4	2	4	5	3	4	3	3	4
10	1	3	4	1	4	1	3	4	2	4	1	2	4
11	4	4	4	2	5	5	4	1	3	4	3	3	5
12	4	4	1	4	4	4	4	4	4	4	4	4	4
13	2	2	4	3	4	4	3	4	3	3	4	3	4
14	3	4	5	4	4	3	3	4	3	4	3	2	4
15	3	3	5	3	4	3	3	4	3	4	3	4	5
16	4	5	5	3	4	5	3	4	4	4	4	3	4
17	2	2	4	2	2	2	3	4	2	4	2	1	4
18	1	3	4	1	3	2	3	4	2	3	2	1	3
19	2	3	4	2	3	1	2	4	1	4	1	2	4
20	4	3	3	3	4	1	3	3	2	3	3	2	4

21	3	3	3	3	3	3	3	3	3	3	3	3	3
22	4	3	5	2	3	2	2	5	4	4	2	2	5
23	1	4	5	2	4	1	1	3	2	3	1	1	4
24	1	2	5	1	2	1	2	5	2	2	2	1	5
25	1	3	5	2	5	1	3	5	1	5	2	3	5
26	1	4	4	1	5	1	3	5	1	4	2	2	5
27	1	3	5	1	4	1	3	5	1	5	1	3	5
28	1	3	5	1	5	1	2	4	2	5	3	3	5
29	3	3	3	3	4	2	3	4	3	3	2	3	3
30	1	3	4	1	3	1	3	4	2	4	2	4	5
31	4	2	2	4	5	1	2	2	1	2	1	1	5
32	1	2	4	2	2	1	2	3	1	2	1	3	5
33	1	1	3	1	3	1	1	2	1	1	1	3	3
34	1	3	5	2	5	2	4	5	4	5	2	4	4
35	1	3	5	1	5	1	3	5	4	5	1	3	5
36	2	4	5	2	2	1	2	4	2	3	1	3	5
37	1	4	5	1	5	1	3	5	3	5	3	4	5
38	1	3	5	1	5	1	3	5	1	5	2	3	5
39	2	3	4	2	5	2	3	4	2	4	2	3	4
40	1	3	4	1	4	1	4	5	1	4	1	3	4
41	1	2	4	2	5	1	3	5	2	4	2	3	4
42	1	3	5	1	4	1	2	3	2	4	2	3	5
43	2	4	5	2	5	2	3	5	2	4	2	2	4
44	2	3	4	2	5	2	3	4	2	3	3	2	4
45	1	1	5	3	4	2	3	4	2	4	2	3	5
46	1	3	5	1	1	2	3	3	3	3	3	3	3

47	1	5	5	1	4	2	3	5	2	3	2	2	4
48	2	3	5	3	3	3	4	5	4	5	3	4	5
49	1	4	5	3	5	1	3	4	1	3	3	4	5
50	1	2	4	1	4	1	2	4	1	4	1	3	5
51	3	4	5	3	5	1	3	5	2	5	1	2	5
52	1	2	4	3	5	2	3	4	2	4	3	4	4
53	2	3	5	1	4	3	4	5	2	3	2	2	4
54	1	3	4	2	4	2	3	4	2	4	2	3	4
55	1	2	3	1	4	2	3	4	1	3	1	2	3
56	2	3	4	1	4	1	2	4	2	4	2	2	5
57	2	3	5	2	5	2	3	5	3	5	3	4	5
58	1	2	4	1	3	2	3	4	1	1	1	2	5
59	2	3	4	2	4	2	3	3	4	4	2	5	5
60	1	1	2	3	3	2	3	4	3	3	3	3	3
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113	1	3	5	3	5	2	3	5	2	4	3	3	5
114	4	2	1	1	4	1	4	5	1	5	3	4	5

8.11 Ethics Approval

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HUMAN RESEARCH ETHICS COMMITTEE (TASMANIA) NETWORK

UTAS

28 April 2016

Dr Rouzbeh Abbassi
National Centre for Maritime Engineering and Hydrodynamics
University of Tasmania

Student Researcher: T M Rabiul Islam

Sent via email

Dear Dr Abbassi

Re: MINIMAL RISK ETHICS APPLICATION APPROVAL
Ethics Ref: **H0015701 - Applications of Human Factor Risk Assessment to the Maintenance Operation in Marine Systems**

We are pleased to advise that acting on a mandate from the Tasmania Social Sciences HREC, the Chair of the committee considered and approved the above project on 28 April 2016.

This approval constitutes ethical clearance by the Tasmania Social Sciences Human Research Ethics Committee. The decision and authority to commence the associated research may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance from other organisations or review by your research governance coordinator or Head of Department. It is your responsibility to find out if the approval of other bodies or authorities is required. It is recommended that the proposed research should not commence until you have satisfied these requirements.

Please note that this approval is for four years and is conditional upon receipt of an annual Progress Report. Ethics approval for this project will lapse if a Progress Report is not submitted.

The following conditions apply to this approval. Failure to abide by these conditions may result in suspension or discontinuation of approval.

1. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval, to ensure the project is conducted as approved by the Ethics Committee, and to notify the Committee if any investigators are added to, or cease involvement with, the project.

A PARTNERSHIP PROGRAM IN CONJUNCTION WITH THE DEPARTMENT OF HEALTH AND HUMAN SERVICES

2. Complaints: If any complaints are received or ethical issues arise during the course of the project, investigators should advise the Executive Officer of the Ethics Committee on 03 6226 7479 or human.ethics@utas.edu.au.

3. Incidents or adverse effects: Investigators should notify the Ethics Committee immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.

4. Amendments to Project: Modifications to the project must not proceed until approval is obtained from the Ethics Committee. Please submit an Amendment Form (available on our website) to notify the Ethics Committee of the proposed modifications.

5. Annual Report: Continued approval for this project is dependent on the submission of a Progress Report by the anniversary date of your approval. You will be sent a courtesy reminder closer to this date. **Failure to submit a Progress Report will mean that ethics approval for this project will lapse.**

6. Final Report: A Final Report and a copy of any published material arising from the project, either in full or abstract, must be provided at the end of the project.

Yours sincerely

Katherine Shaw
Executive Officer
Tasmania Social Sciences HREC

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